Simulation of Noise Characteristics Caused by Discretized Traps in MOSFETs

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Abstract — **Simulation methods for the flicker noise caused by discretized traps in gate insulators of scaled-down MOSFETs were studied. An analytical approach for statistical calculation and a partial Monte Carlo method for interpreting the effects of the noise sources were implemented in a device simulator. The analytical method successfully reproduced the fluctuations observed in the measured noise characteristics. The partial Monte Carlo method was used to clarify the roles of the carrier and mobility fluctuations.**

Keywords-flicker; noise; MOSFET; trap; Monte Carlo; simulation

I. INTRODUCTION

The characteristics of the flicker noise caused by traps in the gate insulator should be taken into consideration in the design of the analog circuits of MOSFETs. It has been reported that the characteristics fluctuate more as the gate area is scaled down because the Lorentzian feature of each trap becomes significant [1][2]. Analytical model for the flicker noise of MOSFETs has been used for various studies such as the extraction of the trap density in gate insulators and the construction of compact models for circuit simulation [3]. The model is useful, but it is difficult to incorporate the actual distribution of physical values in MOSFETs. The impedance field method, which utilizes the small signal analysis framework to treat the frequency dependence of noise, is applicable to actual device structures [4], but it is often troublesome to incorporate the complicated mechanisms of the noise sources. The Monte Carlo method is superior for incorporating the noise sources based on individual physical mechanisms [5]. However, its application to the low frequency region is difficult because a majority of the computation time is consumed in treating phonon scattering events that mainly cause thermal noise. In this study, practical device simulation techniques using the analytical model and the Monte Carlo method are presented to study the influence of discretized traps on noise characteristics.

II. DEVICE SIMULATION USING AN ANALYTICAL MODEL

Figure 1 shows a schematic of device simulation using an analytical model. The spectrum for the drain current noise $S_{ID}(f)$ is calculated by summing components with the tunneling time τ_i for each trap i [3]. The traps are allocated in real and energy spaces by using random numbers. The physical values in the expression for each trap are obtained by device simulation in a self-consistent manner. For instance, the carrier density of $N_{S,i}$ and the mobility μ_i for trap i are obtained by searching the nearest grid on the interface. The charge of the traps is fed back to the Poisson equation. The mobility is modulated by the electric field generated by the charge of the traps. Figure 2 shows the distribution of the tunneling time for 1s and 1 μs in the gate insulator, as examples. The time depends on the energy level and the distance from the surface rather than on the potential drop in the insulator V_{OX} because the gate insulator is relatively thick and the gate voltage is not high in the present study. To obtain the noise spectrum in the range of 1 Hz to 1 MHz, the traps should be distributed in the region specified in the figure. In the device simulation, tunneling between the gate electrode and traps is also included.

Figure 3 shows the simulated drain current versus gate voltage curves together with actual measurements of nMOSFETs and pMOSFETs. The impurity profile is obtained using our process simulator. Surface quantization (SQ) is implemented by a simplified density gradient method [6]. The average distribution of the traps is determined in order to reproduce the threshold voltage. The drain current of pMOSFET is smaller than that of nMOSFETs with the same gate bias; therefore, the gate bias of pMOSFETs should be higher than that of nMOSFET to measure the noise spectrum in the same drain current condition. This affects the gate length dependence of the noise characteristics as shown below.

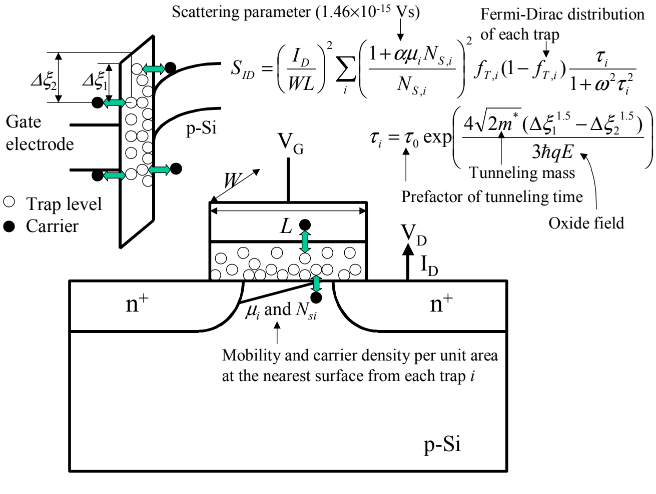

Fig. 1. Schematic of the analytical model for discretized trap distribution.

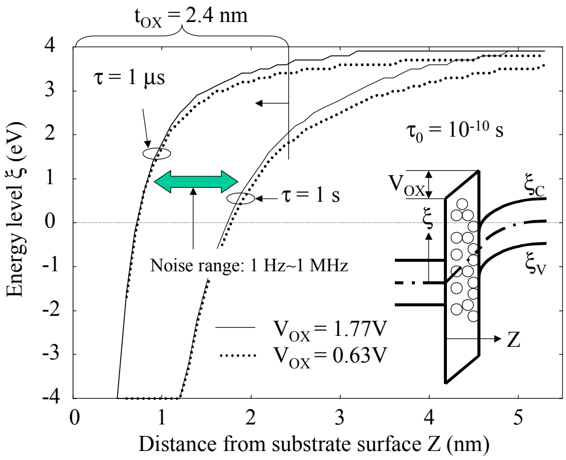

Fig. 2. Distribution of tunneling time in the gate insulator.

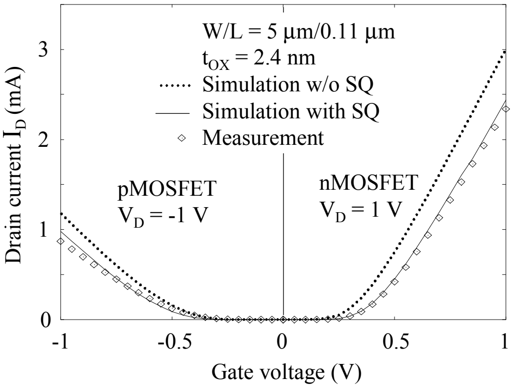

Fig. 3. Drain current versus gate voltage for nMOSFETs and pMOSFETs.

Figures 4 and 5 show flicker noise characteristics for nMOSFETs and pMOSFETs with relatively long channels. Simulations were carried out for ten different of trap distributions. The difference in the gate length dependence of nMOSFETs and pMOSFETs is reproduced. The gate length dependence is smaller for pMOSFETs than for nMOSFETs because the applied gate voltage is larger for pMOSFETs than for nMOSFETs when the drain current is the same. The drain current noise spectrum is proportional to the inversion carrier density per unit area in the strong inversion condition. As a result, the spectrum becomes insensitive to V_G. Statistical fluctuation of the noise characteristics is of little significance because the number of traps contributing the flicker noise feature is sufficiently large. The fluctuation of nMOSFETs is slightly larger than that of pMOSFETs. This is because the carrier density per unit area in nMOSFETs is smaller than that in pMOSFETs when the drain current is the same. Therefore, capture and emission events take place less frequently and the flicker characteristics caused by the events fluctuate.

Figures 6 and 7 show noise characteristics for short-channel devices. The fluctuation of the noise characteristics becomes significant, because the Lorentzian feature of each trap contributing to the flicker noise characteristics becomes pronounced as the total number of traps is reduced in the gate insulator of the scaled-down devices.

The simulation results with the analytical model successfully reproduce the noise characteristics measurements for nMOSFETs and pMOSFETs for different gate lengths, and the computational time is the same as that in the usual drift-diffusion model. Therefore, the present approach with the analytical model is suitable for the statistical study of the noise characteristics of short-channel MOSFETs.

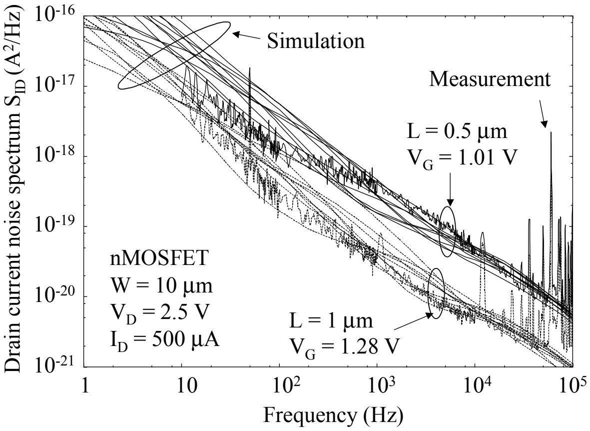

Fig. 4. Noise characteristics of long-channel nMOSFETs.

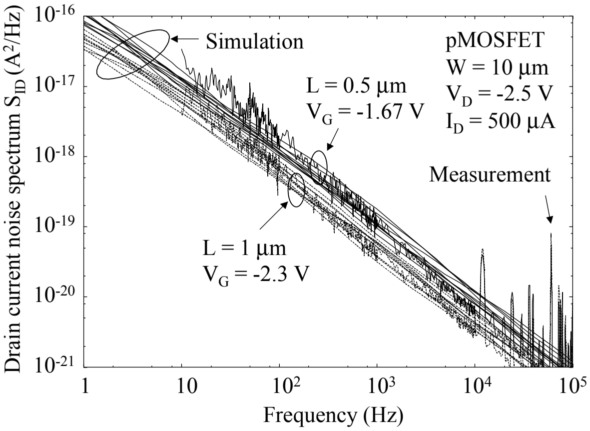

Fig. 5. Noise characteristics of long-channel pMOSFETs.

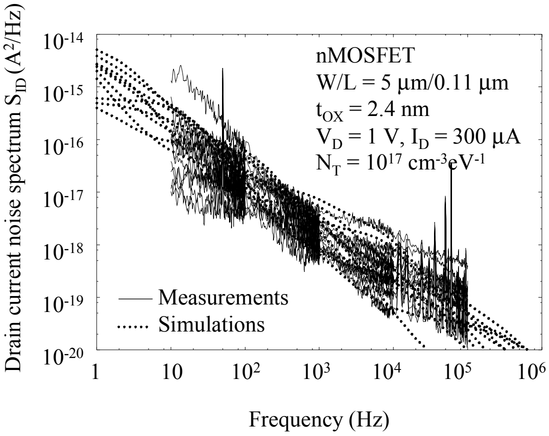

Fig. 6. Noise characteristics of short-channel nMOSFETs.

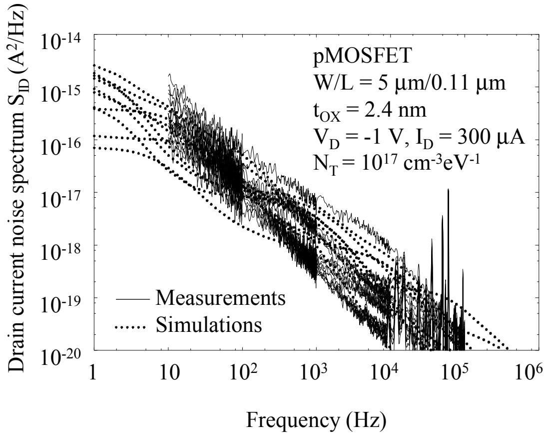

Fig. 7. Noise characteristics of short-channel pMOSFETs.

III. DEVICE SIMULATION WITH THE PARTIAL MONTE CARLO METHOD

Using the discretized trap distribution, the Monte Carlo (MC) method is partially applicable in the framework of the transient simulation in the drift-diffusion model or the hydrodynamic model. The time interval δt for the capture and emission events is determined by using a random number *rnd* and the tunneling time τ_i. This approach is similar to that employed for scattering events in the usual MC code [7]. High-frequency events, such as phonon, impurity, and surface-roughness scattering in the present time scale, are taken into account in the continuity equation. The change of the number of carriers is fed back to the generation-recombination (GR) term and the charge density of the ionized traps is fed back to the Poisson equation. The Fermi-Dirac statistic is automatically introduced by adopting the rejection method according to the occupancy of traps.

The MC method gives the transition of the drain current *Id(t)* as shown in Fig. 8. Figure 9 shows the noise characteristics obtained by the Fourier transform of *Id(t).* The results obtained with feedback to only GR are significantly lower than those obtained with full feedback. This means that fluctuations of potential and mobility through the electric field are dominant rather than the fluctuation of the number of carriers. The result obtained with the analytical method and the same tunneling time model for the same discretized trap distribution is also shown in the figure. The difference relative to the results of the MC method with the full feedback might be caused by the ambiguity in the treatment of the changes in the number and the mobility of carriers in the analytical model. However, the analytical approach is useful for actual analysis; therefore, calibration for the trap density and scattering parameter is indispensable.

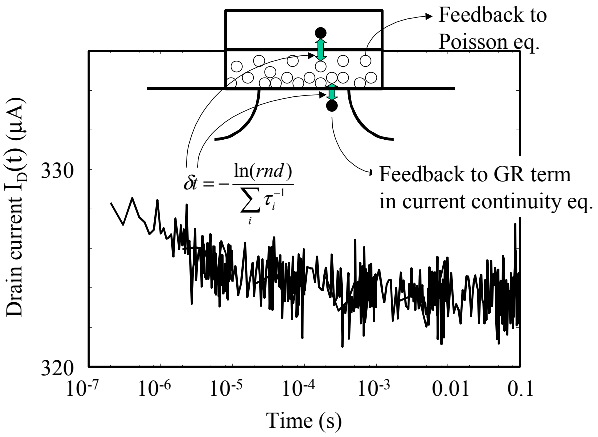

Fig. 8. Transient drain current obtained by the Monte Carlo method.

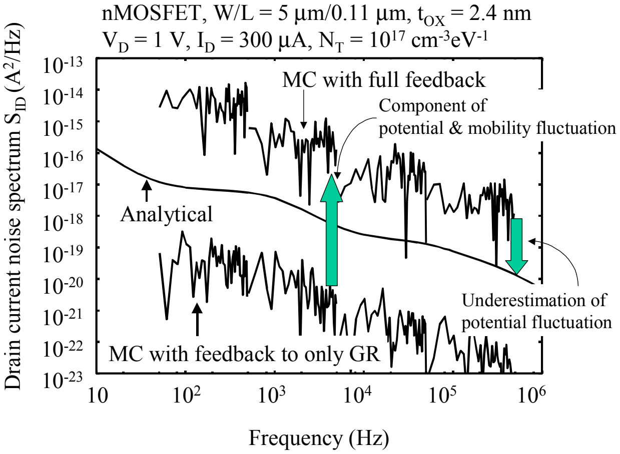

Fig. 9. Noise spectrum obtained by the Monte Carlo method.

IV. SUMMARY

Practical approaches for using a device simulator to the influence of discretized traps in the gate insulator of MOSFETs on the noise characteristics in the device simulator were presented. The analytical approach was shown to be a powerful tool for evaluating the worst case of the noise characteristics, and the partial Monte Carlo method was found to be suitable for interpreting the physical mechanism for responsible for the noise characteristics.

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