

A TCAD-SPICE Simulation Framework for Quantitative Evaluation of MOSFET Properties from SEM Transient Signals

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Abstract— To enable early detection of “invisible” defects, which are increasing with 3D integration, inline electrical testers are highly desired. In this study, we developed a simulation framework using TCAD-SPICE mixed-mode simulation to quantitatively evaluate device electrical properties from scanning electron microscope (SEM) transient signals. Applying this framework to planar MOSFETs, we successfully reproduced experimental data showing that the dependence on threshold voltage and oxide thickness is clearly reflected in the transient signals.

Keywords—3D integration, inline electrical testers, TCAD-SPICE mixed-mode simulation, scanning electron microscope.

I. INTRODUCTION

With the advance of three-dimensional (3D) integration in semiconductor devices, the risk of “invisible” defects that are difficult to detect using traditional dimensional metrology is increasing during the manufacturing process. These invisible defects are often undetected until final electrical testing. This makes it difficult to identify the responsible process step and to improve yield, thereby drastically prolonging the turnaround time. There is a strong demand for inline electrical testers capable of early detection of electrical failures.

Against this backdrop, a scanning electron microscope (SEM)-based electrical measurement method has been developed, showing that the transient secondary electron (SE) signals correlate with the equivalent oxide thickness (EOT) and size of MOS capacitors [1]. To extend this measurement method across various manufacturing processes, a calibration curve representing the relationship between device characteristics and transient signals must be established in advance. However, building these calibration curves solely from experimental data requires significant time and cost. Therefore, simulation capable of quantitatively predicting electrical properties from the transient signals is required.

Previously, a framework integrating a Monte Carlo (MC)-based e-beam simulator with a Technology Computer-Aided Design (TCAD) simulator has been reported [2]. This framework enables the evaluation of charging states induced by electron-beam irradiation using the Poisson equation and the prediction of voltage contrast images. However, simulating microsecond-scale transient signals using the MC method requires large computational resources and time. Furthermore, since the current through the device and the parasitic capacitance vary over time during electron-beam irradiation, it is necessary to solve not only the Poisson equation but also the time-dependent carrier transport equations.

To overcome these challenges, we developed a TCAD-SPICE mixed-mode simulation framework. SPICE models the SEM measurement principle using an equivalent circuit, while TCAD solves the electrostatic potential and carrier concentration distributions inside the device. We applied this framework to planar MOSFETs to simulate transient signals. The objective of this study is to estimate transient signals using this framework. Furthermore, we demonstrate that device electrical properties can be quantitatively evaluated from these signals through successful reproduction of experimentally measured signals.

II. METHOD

A. Simulation Framework for SEM Transient Signals

Our simulation framework is based on the SEM measurement principle shown in Fig. 1. When a pulsed electron beam current (I_p) irradiates a contact plug, SEs are emitted, generating an injection current (I_{inj}) into the device. Under irradiation conditions where the SE yield exceeds unity, I_{inj} causes charge accumulation in the capacitance beneath the plug, leading to a positive surface potential (V_S) of the plug. This V_S acts as a bias voltage that induces leakage current. Ultimately, when the leakage current balances with I_{inj} , V_S saturates.

In this measurement method, two mechanisms determine the number of SEs reaching the detector: a potential barrier in space [3] and an energy filter [4]. First, depending on the influence of V_S and the potentials of surrounding patterns, a potential saddle point may be formed in the space above the device. Letting V_ϕ denote the potential at this saddle point, the difference $V_B (= V_S - V_\phi)$ serves as the spatial potential barrier for the SEs. Low-energy SEs that cannot overcome V_B return to the plug surface. In contrast, high-energy SEs overcome V_B and escape into the vacuum. Letting I_{SE} denote the current of these escaping SEs, the injection current into the device is expressed as $I_{inj} = I_{SE} - I_p$. Next, an energy filter biased at a filter voltage (V_{EF}) is installed in front of the detector. While the emitted SEs have an energy distribution $N(E)$, only SEs that can overcome both V_B and $V_S + V_{EF}$ reach the detector and contribute to the detected current (I_{det}). As V_S rises due to electron-beam irradiation, these potential barriers become higher, which consequently causes a decrease in I_{det} . Eventually, as V_S saturates, I_{det} also reaches a saturation value. The decay and saturation behavior of this I_{det} transient signal effectively reflects the underlying electrical properties of the device.

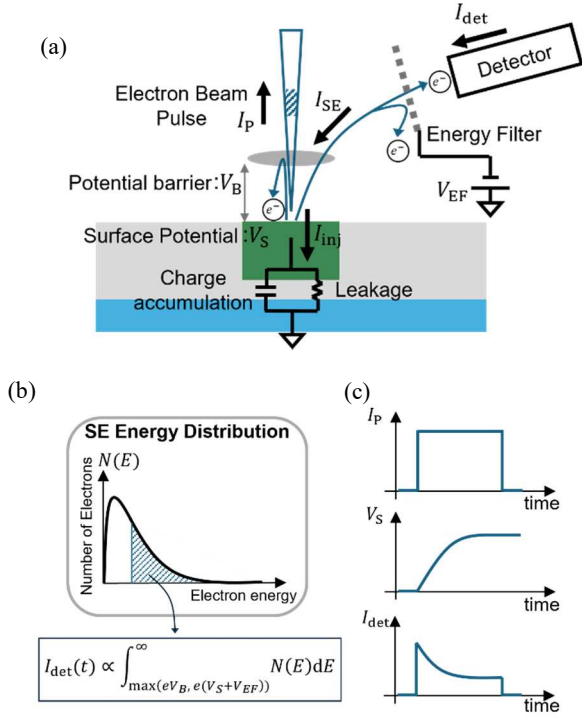


Fig. 1. Principle of measuring electrical properties using a pulsed electron beam. (a) Schematic of the measurement setup. (b) SE energy distribution ($N(E)$), where only SEs overcoming the energy barrier are detected. (c) Pulsed electron beam current (I_p), surface potential (V_S), and detected current (I_{det}).

Figure 2 illustrates the architecture of the proposed TCAD-SPICE mixed-mode simulation framework for reproducing the measurement principle described above. In this framework, the SEM measurement principle is represented by SPICE model and coupled with TCAD, which calculates the transient electrostatic potential and carrier transport inside the device. The TCAD equations (Poisson and carrier transport equations) and the SPICE circuit equations are solved self-consistently. This framework enables the simulation of transient signals directly from the device structure.

Figure 3 shows the coupling between the SPICE equivalent circuit and the TCAD device model at the plug node. V_S is determined at each time step such that Kirchhoff's current law is satisfied at this node. The balance between I_{inj} and the leakage current flowing through the device determines the transient behavior of V_S and I_{det} .

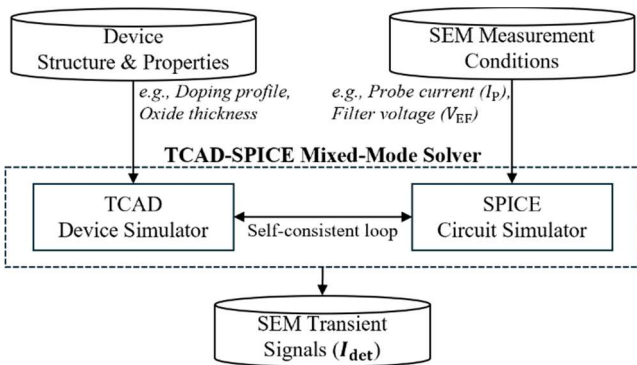


Fig. 2. The proposed TCAD-SPICE mixed-mode simulation framework.

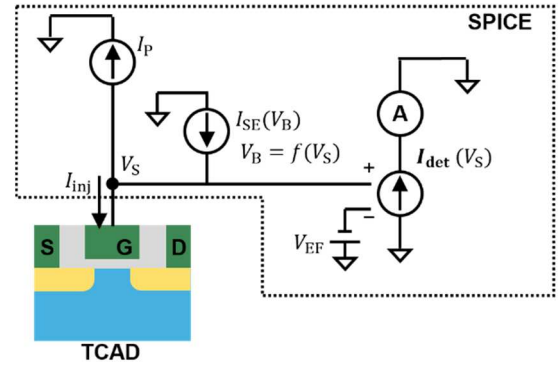


Fig. 3. Coupling between the SPICE equivalent circuit and the TCAD device at the plug node.

B. Device Modeling and Experimental Conditions

The proposed framework is validated using a Planar MOSFET. Figure 4 shows the top-view SEM image of the tungsten contact plug and cross-sectional TEM image of the device. The gate electrode is shared by both NMOS and PMOS, and the source diffusion region has a larger area than the drain. Two device variants, low-threshold (LVT) and high-threshold (HVT), are implemented by adjusting the channel doping concentration.

Figure 5 illustrates the TCAD model of the MOSFET configured based on this device. By modifying only the channel doping, LVT and HVT NMOS devices are reproduced. Figure 6 shows the transfer characteristics obtained from the TCAD simulation and nano-prober [5] measurements. The threshold voltage is defined as the gate voltage at a drain current of 1×10^{-8} A, yielding threshold voltages of 0.04 V for LVT and 0.24 V for HVT. These results indicate that the device model captures the difference in threshold voltage between LVT and HVT devices observed in the experimental characteristics.

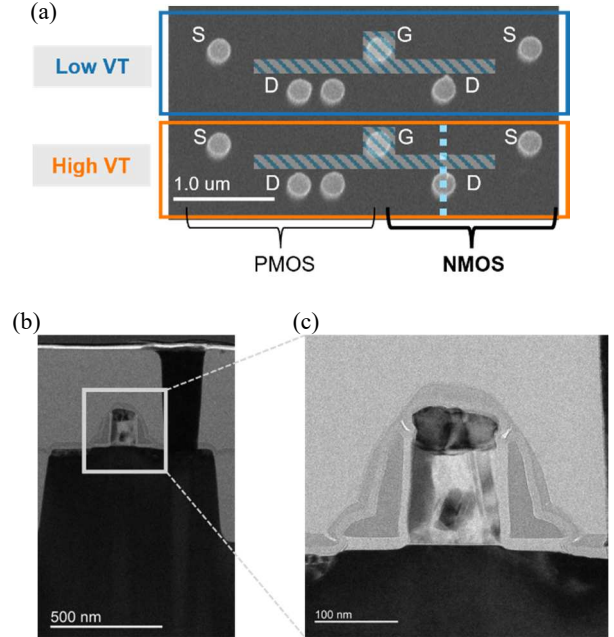


Fig. 4. (a) Top-view SEM image of the contact plug region. The shaded area indicates the location of the underlying poly-Si gate. The dashed line indicates the cross-sectional position for the TEM image shown in (b). (b) Cross-sectional TEM image of the planar MOSFET, showing the gate electrode and the drain contact plug. (c) Enlarged TEM image of the boxed region in (b) around the gate.

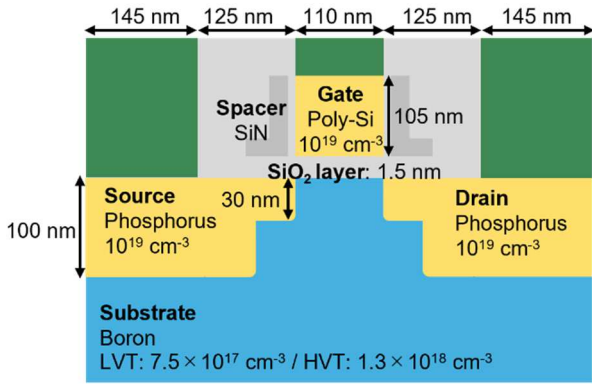


Fig. 5. Schematic device structure of the planar n-MOSFET used in the simulation. The gate width is 420 nm. LVT and HVT devices are reproduced by modifying the channel doping concentration.

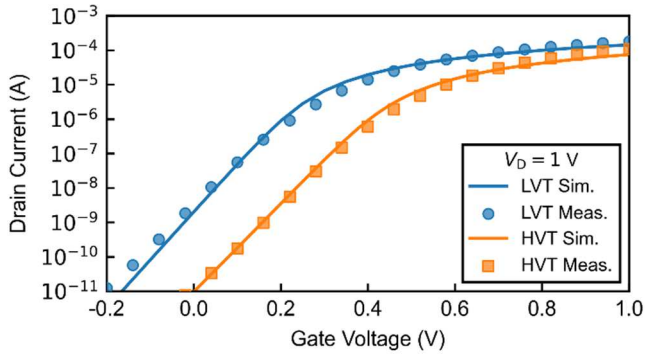


Fig. 6. Transfer characteristics of LVT and HVT n-MOSFETs obtained from TCAD simulations and nano-prober measurements.

In this study, the transient signals at the drain and gate contact plugs were measured and simulated. The TCAD simulation employed the Poisson and drift-diffusion equations. The SE yield of the plug was set to 2.0, and I_p is 2 nA. For gate measurements, leakage current under high electric fields was modeled using Fowler-Nordheim tunneling [6] in SPICE. The oxide voltage was derived from the surface potential, and the tunneling current was calculated as a function of this voltage. The current contributing to gate charging was then obtained by subtracting the tunneling current from I_{inj} .

In actual measurements, plugs without electron-beam irradiation are electrically floating. However, in this study, they were approximated as grounded for simplicity, considering the large source diffusion area and the significant gate capacitance shared between NMOS and PMOS.

In the present measurements, no saddle-point potential was formed, and an energy filter was employed. I_{det} was modeled based on the energy distribution of SEs and the transmission characteristics of the filter. To establish this relationship, the filter voltage was swept under a non-charging condition, where V_S remains nearly constant, and I_{det} reflects the SE yield of the tungsten plug. The resulting curve (Fig. 7) was then converted into a relationship between V_S and I_{det} . This relationship was then approximated by a sigmoid function.

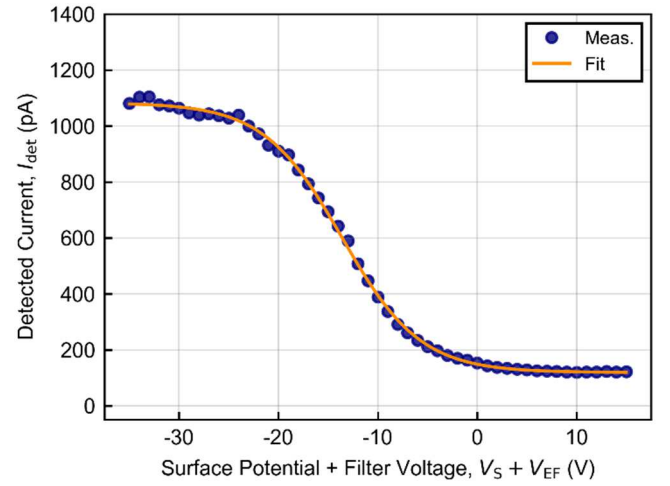


Fig. 7. Relationship between surface potential (V_S) and detected current (I_{det}) derived from the energy filter characteristics. The measured I_{det} is shown with fitted solid lines.

III. RESULTS AND DISCUSSION

A. Threshold Voltage Dependence in Drain Contact Measurements

Figures 8(a) and (b) show the measured and simulated I_{det} transient signals for LVT and HVT devices during drain contact plug measurements. In the initial stage of electron-beam irradiation, I_{inj} into the plug exceeds the leakage current between the source and drain, leading to charge accumulation in the parasitic capacitance and an increase in V_S . As V_S increases, fewer SEs can pass through the energy filter biased at -28 V, resulting in a decay of I_{det} . Subsequently, the increase in V_S (i.e., the drain voltage) enhances the electric field between the drain and source, which increases the leakage current. When the leakage current balances I_{inj} , both V_S and I_{det} reach saturation. As shown in Fig. 5, the LVT device exhibits a larger leakage current than the HVT device. Therefore, the current balance is achieved at a lower V_S for the LVT device, resulting in a higher saturation level of the I_{det} compared to the HVT device. The proposed framework successfully reproduces the difference in the saturation level of the transient signals corresponding to the threshold voltage variation observed in the SEM measurements.

B. Oxide Thickness Dependence in Gate Contact Measurements

Figure 9 shows the measured and simulated I_{det} transient signals for the LVT device at the gate contact with an oxide thickness of 1.5 nm. In addition, the simulation result for a thickness of 2.0 nm, representing a change in oxide thickness, is shown as a dashed line. Under electron-beam irradiation at the gate, the gate capacitance is charged, resulting in an increase in V_S . As V_S increases, the electric field across the oxide becomes stronger, leading to an exponential increase in the tunneling current. When the tunneling current balances I_{inj} , V_S reaches saturation, and the I_{det} also saturates.

For the thinner oxide (1.5 nm), the tunneling current increases more readily than in the 2.0 nm case. As a result, current balance is achieved at a lower V_S , leading to a higher saturation level of I_{det} compared to the thicker oxide case. These results demonstrate that the proposed simulation framework can not only reproduce the measured signal but

also predict the impact of oxide thickness variations on the transient signals.

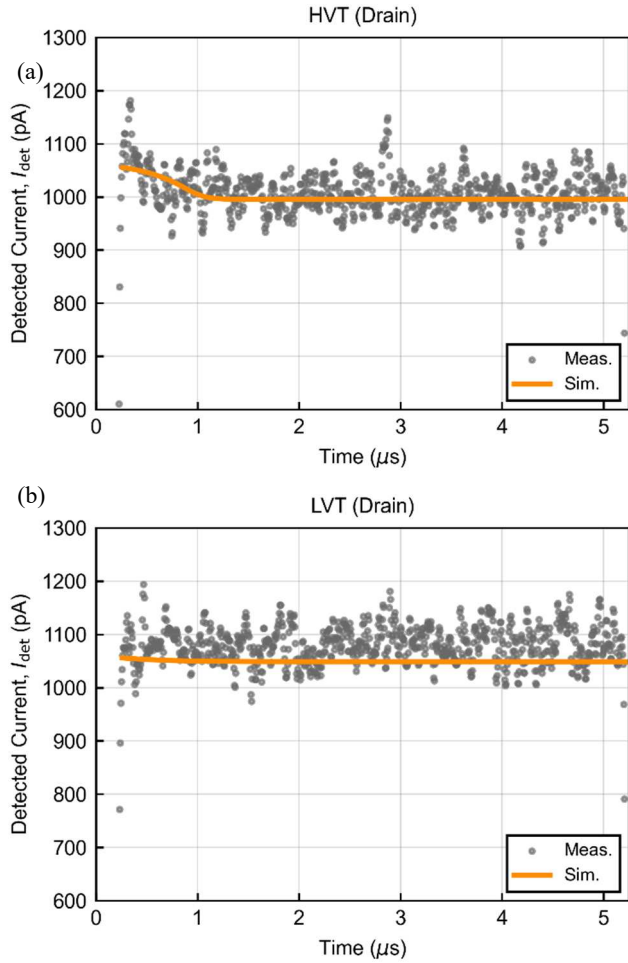


Fig. 8. Measured and simulated transient signals of detected current (I_{det}) as a function of irradiation time at the drain contact for (a) LVT and (b) HVT devices. The experimental data are shown as gray markers, and the simulated results are shown as solid lines.

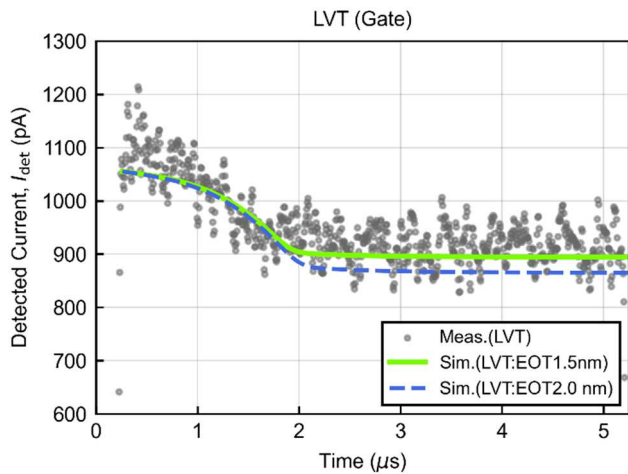


Fig. 9. Measured and simulated transient signals of detected current (I_{det}) as a function of irradiation time at the gate contact for different oxide thicknesses. The experimental data are shown as markers, and the simulation results are shown as solid and dashed lines corresponding to different conditions.

IV. CONCLUSION

This study presents a TCAD–SPICE simulation framework for quantitatively evaluating device electrical properties and their effects on SEM transient signals in inline measurements. Validation using planar MOSFETs demonstrates that the saturation level of the transient signal at the drain contact reflects the leakage current between the source and drain and depends on the threshold voltage, which is accurately reproduced by the proposed framework. For gate measurements, the framework also captures the effect of oxide thickness variations on the transient response and enables prediction of their impact on the detected signal.

These results indicate that the proposed framework can quantitatively predict the relationship between device parameters and SEM transient signals based on physical modeling, without relying on extensive experimental data. This approach is expected to contribute to the development of inline electrical characterization for advanced 3D integrated devices.

Future work includes the development of a more rigorous simulation framework that accounts for additional device physics, such as floating-node potential variations and a more accurate treatment of tunneling currents within TCAD. In addition, comparison with experimental data under conditions where a saddle-point potential is formed will be conducted, and the framework will also be extended to 3D structures and a wider range of defects and variability sources.

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