

SPICE Modeling Method of Reverse Recovery Based on TCAD Analysis

Emiru Baba¹, Shigeru Nakajima², Tsuyoshi Kachi², Takuma Hara², Kozo Kinoshita¹

Advanced Semiconductor Device Development Center

Toshiba Electronic Devices & Storage Corporation

¹1, Toshiba-cho, Komukai, Saiwai-ku, Kawasaki, Kanagawa, Japan, ²1-1, Iwauchi-machi, Nomi, Ishikawa, Japan

e-mail: emiru.baba.h20@mail.toshiba

Abstract—We propose a TCAD-based, waveform-level SPICE model that reproduces the reverse recovery behavior of power MOSFETs. The reverse recovery current is decomposed into an excess carrier component stored in the body diode and a displacement-current component associated with parasitic capacitances. These components are mapped independently to the body diode junction capacitance and drain-source capacitance in SPICE, enabling independent control of the recovery peak and tail. The model reproduces the TCAD-derived reverse recovery waveform and associated transient characteristics with normalized RMS errors below 5%.

Keywords— Reverse recovery, SPICE modeling, TCAD, Power MOSFET, Semiconductor physics, Waveform-level modeling, Transient analysis

I. INTRODUCTION

Accurate modeling of reverse recovery current is essential for predicting the efficiency and switching behavior of converters employing power MOSFETs [1-3]. Both its magnitude and waveform strongly affect switching loss and can trigger self-turn-on in synchronous rectification circuits [4-5]. Reliable prediction of reverse recovery is therefore indispensable in early-stage device development.

In conventional compact-model flows, TCAD-derived DC characteristics, including output, transfer, and static body-diode characteristics, are first fitted to construct SPICE models. However, even after accurate DC fitting, the reverse recovery waveform often exhibits substantial deviation from TCAD mixed-mode results. Fig. 1 shows that the SPICE model still exhibits a noticeable mismatch in the reverse recovery waveform compared with the TCAD results. To reduce this mismatch, reverse recovery is often characterized solely by the integral reverse recovery charge Q_{rr} , sacrificing waveform-level accuracy [6]. Although SPICE macro-models can reproduce reverse recovery waveforms, they require complex formulations, thereby compromising model simplicity [7].

Here, we present a waveform-oriented, physically guided SPICE model for reverse recovery in power MOSFETs that assigns TCAD-derived current components to distinct compact-model elements. This approach enables independent control of the recovery peak and tail, reproduces the reverse recovery waveform and associated transients, and improves interpretability compared with conventional fitting approaches.

II. SIMULATION METHOD

Fig. 2a shows the Double-Pulse Test (DPT) circuit used to evaluate reverse recovery. We analyzed the reverse recovery using LTspice (Analog Devices, Inc.) and Synopsys TCAD mixed-mode simulation. The SPICE simulations used a

BSIM3v3.3 compact model, whereas the TCAD simulations used a physics-based model, with identical circuit topologies in both. We adjusted the gate resistance to achieve a drain-current slew rate of $di/dt = 300$ A/ μ s. The supply voltage was fixed at 40 V. As shown in Fig. 2b, during the first pulse, a gate voltage is applied to the low-side MOSFET while the high-side MOSFET remains off. When the low-side MOSFET turns off, the inductor current commutates to the high-side body diode. On the subsequent turn-on of the low-side MOSFET, reverse recovery current is induced by the high-side MOSFET.

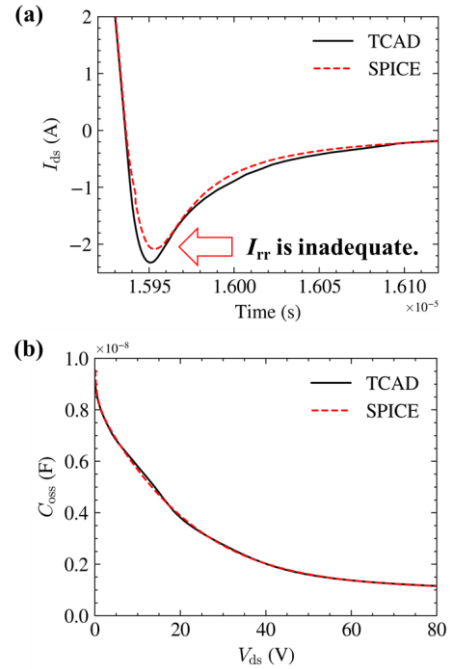


Fig. 1. (a) Reverse recovery current waveform and (b) C_{oss} - V_{ds} characteristics of the SPICE model after DC fitting, compared with TCAD results.

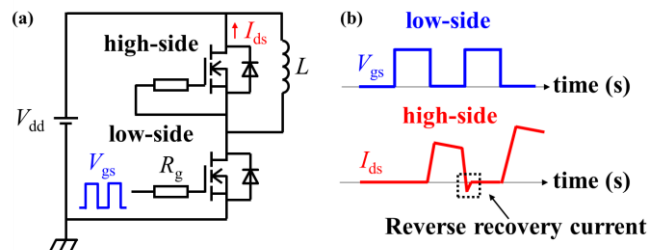


Fig. 2. (a) Double-Pulse Test (DPT) circuit used for reverse recovery analysis and (b) schematic illustration of the DPT operation.

III. RESULTS AND DISCUSSION

A. Conventional Reverse-Recovery Modeling

Fig. 3 shows the conventional SPICE equivalent circuit of the diode [8]. It consists of a voltage-controlled current source in series with an internal resistance R_s , together with a junction capacitance C_j dominant under reverse-bias and a diffusion capacitance C_D dominant under forward-bias.

In conventional compact models, reverse recovery is mainly controlled by the diffusion capacitance C_D through a single transit-time parameter TT , as described in (1) and (2). Although this captures charge storage in the forward-biased body diode, waveform controllability is limited. In particular, the reverse recovery peak and tail duration cannot be adjusted independently, making TCAD-derived waveforms difficult to reproduce over varying conditions (Fig. 4).

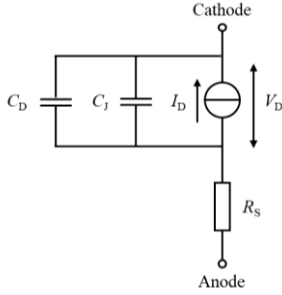


Fig. 3. Equivalent circuit of the SPICE diode model.

$$Q_D = TT \cdot I_D \quad (1)$$

$$C_D = TT \cdot \frac{dI_D}{dV_D} \quad (2)$$

In the overall SPICE MOSFET model shown in Fig. 1, the reverse recovery current I_{rr} is expressed as the sum of current components related to the drain-source and gate-drain capacitances, namely $I_{C_{ds}}$ and $I_{C_{gd}}$, as given in (3). However, this model exhibits a noticeable mismatch in the reverse recovery waveform.

$$I_{rr}^{dc} = I_{C_{ds}} + I_{C_{gd}} \quad (3)$$

To reduce the mismatch of the conventional model, the transit-time parameter TT was increased to match the TCAD-derived peak value of reverse recovery current. The resulting SPICE model is shown in Fig. 5. While this preserves the already calibrated C_{oss} - V_{ds} characteristics, it introduces an undesired bump in the reverse recovery waveform. This bump arises because the diffusion-capacitance-related current component I_{CD} is sharp and short-lived (Fig. 6).

When the transit-time parameter TT is increased, the reverse recovery current becomes dominated by the diffusion-capacitance-related component I_{CD} , as expressed in:

$$I_{rr}^{conv} = I_{C_{ds}} + I_{C_{gd}} + I_{CD} \quad (4)$$

Previous work has also reported that a diode model using TT as the sole reverse-recovery-related parameter is insufficient to fully capture reverse-recovery behavior under high-frequency operation, with the discrepancy becoming more pronounced at 1 MHz [9]. Therefore, simply introducing C_D is insufficient to achieve accurate waveform-level fitting.

In this study, for example in Fig. 6, the contribution of the diffusion capacitance C_D was evaluated by intentionally setting the drain-source capacitance C_{ds} to a negligibly small value. This decomposition is not a rigorous physical separation; in particular, the contribution of parasitic gate-drain capacitances C_{gd} may appear in both components.

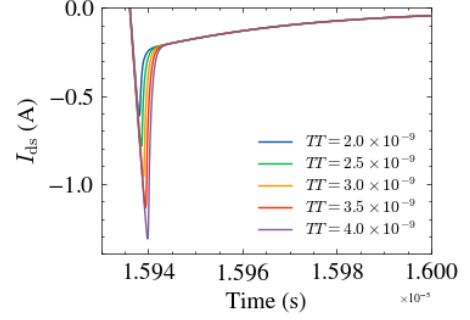


Fig. 4. The diffusion capacitance C_D -based reverse recovery with TT sweep.

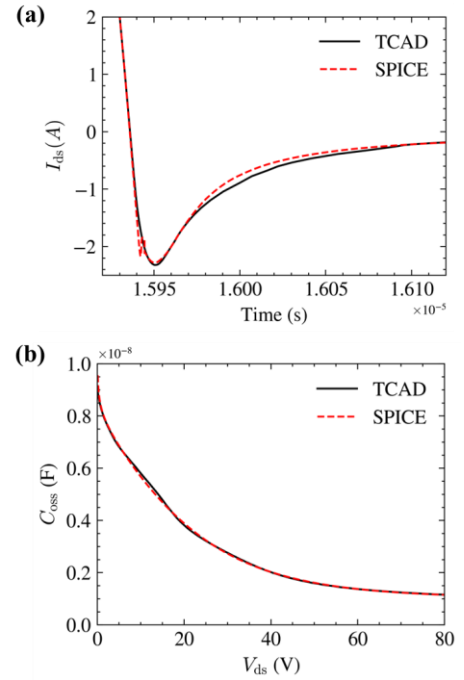


Fig. 5. (a) Reverse recovery waveform of the TT -adjusted SPICE model including the diffusion capacitance C_D , and (b) its C_{oss} - V_{ds} characteristics.

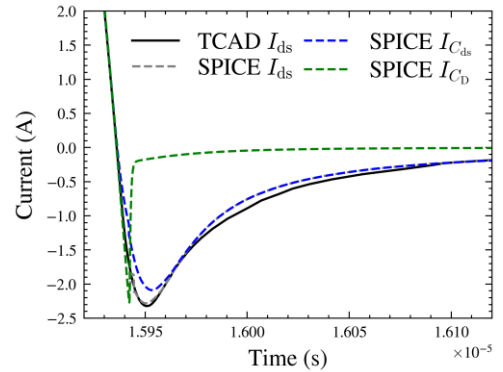


Fig. 6. Approximate decomposition of SPICE current components into C_D -related and C_{ds} -related contributions during reverse recovery.

B. TCAD Analysis of Reverse Recovery

Previous studies have shown that the reverse recovery current of power MOSFETs consists of two physical components [10-12]: removal and recombination of excess carriers accumulated in the body diode during forward conduction, and displacement current associated with charging and discharging of the parasitic output capacitance C_{oss} . Fig. 7 shows the TCAD-derived reverse recovery current I_{ds} decomposed into the excess-carrier removal current in the body diode $I_{Pbody-Drain}$ and displacement currents through the drain-source and gate-drain capacitances, I_{Cds} and I_{Cgd} , respectively.

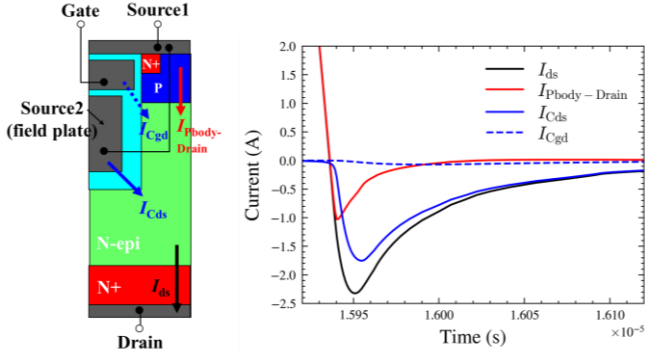


Fig. 7. TCAD-based decomposition of the reverse recovery current into excess-carrier-related and displacement-current components.

C. Physics-Based SPICE Modeling of Reverse Recovery

Based on the TCAD current decomposition, the excess-carrier-related and displacement-current components were modeled independently in SPICE. Rather than using the diffusion capacitance C_D alone to represent excess-carrier storage, we employed the junction capacitance C_J to model the excess-carrier-related current. Although C_J is originally defined as a depletion capacitance, its voltage-dependent charge characteristics provide adjustable parameters, including the zero-bias capacitance C_{j0} , junction potential V_j , and grading coefficient M , as described by (5) and (6) [13]. The capacitance is defined over distinct voltage regions, separated by V_j and the forward-bias depletion capacitance coefficient Fc . These parameters enable flexible control of the charge removal dynamics during reverse recovery. As shown in Figs. 8a and 8b, a smaller M broadens the recovery waveform and lengthens the tail, whereas a larger M sharpens the peak and shortens the recovery time.

The diffusion capacitance C_D is derived from the diffusion charge Q_D , whereas the junction capacitance C_J is defined directly as a voltage-dependent capacitance, from which the depletion charge Q_J is obtained by integration, as expressed in (7). As a result, the diffusion-capacitance-related current is governed primarily by changes in diode current, whereas the junction-capacitance-related current is governed by changes in junction voltage. The nonlinear voltage-dependent charge characteristics of C_J , together with its multiple adjustable parameters, provide greater flexibility in controlling charge removal during reverse recovery.

From a modeling standpoint, this approach does not assert strict physical equivalence between depletion charge and stored excess carriers; rather, it provides an effective compact representation that preserves the TCAD-derived time dependence, amplitude, and voltage-dependent charge removal behavior.

For $V_D < Fc \cdot V_j$,

$$C_J = C_{j0} \cdot \left(1 - \frac{V_D}{V_j}\right)^{-M} \quad (5)$$

Else,

$$C_J = \frac{C_{j0}}{(1 - Fc)^{M+1}} \cdot \left(1 - Fc \cdot (M + 1) + \frac{M \cdot V_D}{V_j}\right) \quad (6)$$

$$Q_J = \int C_J(V_D) dV_D \quad (7)$$

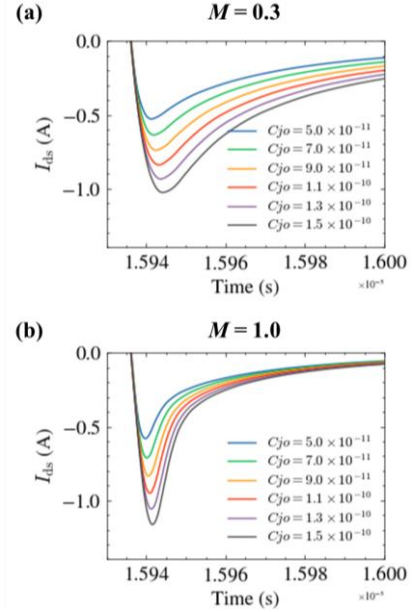


Fig. 8. Reverse recovery waveforms associated with the junction capacitance C_J for (a) $M = 0.3$ and (b) $M = 1.0$, with C_{j0} sweep.

By combining the excess-carrier-related current, the displacement current, and minor tuning using diffusion capacitance C_D as an auxiliary capacitance, the SPICE model reproduces the TCAD-derived reverse recovery waveform (Fig. 9). In this model, the reverse recovery current I_{rr} is explicitly represented as the sum of its constituent components, as expressed in:

$$I_{rr} = I_{Cds} + I_{Cgd} + I_{CJ} + I_{CD} \quad (8)$$

This formulation enables independent control of each current component, allowing accurate reproduction of both the peak and tail characteristics of the reverse recovery waveform.

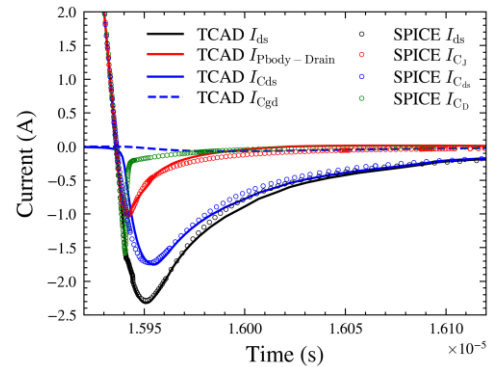


Fig. 9. Comparison of TCAD-derived and SPICE current components, including excess-carrier-related (red) and displacement-current (blue).

After determining the parameters governing the excess-carrier-related current, we adjusted the drain-source capacitance C_{ds} in the SPICE model to reproduce the output-capacitance C_{oss} - V_{ds} characteristics (Fig. 10). To capture the stored-current component contributing to reverse recovery, the diode junction capacitance C_j under reverse bias was incorporated in addition to the drain-source capacitance C_{ds} . As a result, the output capacitance C_{oss} was modeled as the combined contribution of the junction capacitance and drain-source capacitance components. Through this adjustment, the SPICE-derived displacement current associated with C_{ds} showed good agreement with the TCAD-derived displacement current in Fig. 9.

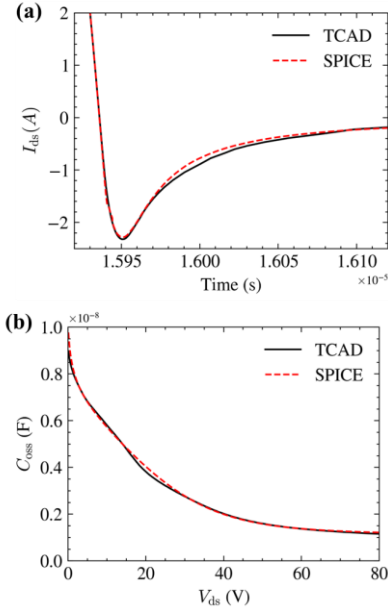


Fig. 10. (a) Reverse recovery waveform and (b) output-capacitance characteristics of the SPICE model obtained by the proposed method.

D. Model Validation

We evaluated the model accuracy using the normalized RMS error defined in (9), where sim_j and $meas_j$ represent the SPICE-simulated and TCAD-simulated values at the j -th data point, respectively, and N is the total number of data points. The evaluation range was 15.92–16.12 μ s for reverse recovery and 0.0–80.0 V for the C_{oss} - V_{ds} characteristic. As summarized in Table 1, the proposed model achieves NRMS errors below 5% for both metrics. In contrast, the after-DC-fitting model in Fig. 1 and the conventional model in Fig. 5, which relies primarily on the diffusion capacitance C_D , exhibit larger errors in reverse recovery.

$$\text{NRMSE (\%)} = 100 \cdot \frac{\sqrt{\sum_{j=1}^N (sim_j - meas_j)^2 / N}}{\sqrt{\sum_{j=1}^N (meas_j)^2 / N}} \quad (9)$$

TABLE I. NRMS ERROR EVALUATION

Models	NRMS Error	
	Reverse recovery (%)	C_{oss} - V_{ds} (%)
SPICE model after-DC-fitting	9.99	1.53
Conventional model	6.91	1.53
This Work	4.54	2.66

IV. CONCLUSION

We developed a TCAD-informed, waveform-level SPICE model for reverse recovery in power MOSFETs. By assigning excess-carrier-related and displacement-current components to distinct SPICE capacitances, the model reproduces reverse recovery waveforms with NRMS errors below 5%. This approach provides a physically interpretable basis for accurate circuit-level transient simulations in power electronic applications within the studied operating range.

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