Dynamic-Carrier-Distribution-Based Compact Modeling of P-i-N Diode Reverse Recovery Effect

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1. Introduction

This paper presents compact modeling of diode reverse recovery effect for SPICE simulation. The reverse recovery effect causes a strong current peak during switching off of power diodes, which results in the largest power dissipation factor in power converters \([1]\). Accurate compact modeling of this phenomenon enables to design more and more efficient power electronic circuits. At the beginning of this work, 2D-device simulation is performed to obtain a target data and to understand the dynamic carrier distribution within the drift layer of a P-i-N power diode with simulation setup shown in Fig. 1 \([2]\). Afterward, the reverse recovery effect is modeled based on the dynamic carrier distribution, and verified with 2D-device simulation results.

2. Remaining Carriers in the N-Drift Region

During the on-state of P-i-N diodes, excess carriers are stored in the N-drift \((i)\) layer. The stored carriers start to run out when the applied bias turns off. During the switch off, running carriers are observed as a displacement current, namely, the reverse recovery effect. However, the carrier dynamics is more complicated as shown in Fig. 2. According to this 2D-device simulation result, most of the stored carriers are remaining in the drift region even after the applied bias reaches to the reverse-biased off-state, while the expanding depletion layer is sweeping out carriers toward the cathode. This carrier dynamics determines the shape of the reverse-recovery current waveforms.

3. Compact Modeling of the Reverse Recovery Effect

In this model, the total diode anode current \(I_a\) including the reverse recovery effect is written as,

\[
I_a (t) = I_{DC} \left(V_{ak} (t)\right) + \frac{dQ_{dep} (t)}{dt} + \frac{dQ_{rr} (t)}{dt}
\]  

(1)

where \(I_{DC}\) is the steady-state diode current and \(Q_{dep}\) is the depletion charge written as \(qAW_{dep}\). \(Q_{rr}\) is the reverse-recovery charge described as,

\[
Q_{rr} (t) = qA \int_{W_{dep}}^{W} p_{rr} (x,t) \, dx
\]  

(2)

where \(W_{dep}\) is the depletion width written as,

\[
W_{dep} \left(V_{ak} (t)\right) = \sqrt{\frac{2\varepsilon_S (V_{bi} - V_{ak} (t))}{qN}}
\]  

(3)

\(p_{rr}\) describes the dynamic carrier distribution in the carrier-storage region \((W_{dep} < x < W)\) as,

\[
p_{rr} (x,t) = p_{n,NQS} (t) \cdot \exp \left(-\frac{x}{L}\right)
\]  

(4)

where \(L\) is the diffusion length. The most important technique in this model is to describe the remaining carriers \(p_{n,NQS}\) which is written as,

\[
p_{n,NQS} (t) = p_{n,NQS} (t - \Delta t) + \frac{\Delta t}{\tau_{rr}} \left[ p_{n0} \left(V_{ak} (t)\right) - p_{n,NQS} (t - \Delta t) \right]
\]  

(5)

where \(\tau_{rr}\) is the recovery time. This technique originates from the carrier-transit-delay-based non-quasi-static effect model \([3]\). \(p_{n0}\) means the injected carrier density from the P+ layer at the sur-
face of the P+/N- junction, which is written as,

\[ p_{r0} \left( V_{ak}(t) \right) = p_{r0} \cdot \exp \left( \frac{qV_{ak}(t)}{nkT} \right) \]  

(6)

With above model equations, dynamic carrier distribution is modeled as shown in Fig. 3, where we call the developed model “HiSIM-Diode”. \( \tau_r \) and \( n \) are main fitting parameters for the reproduction of the reverse recovery current.

4. Verification Results

The developed HiSIM-Diode model has been implemented in a Verilog-A code and tested with commercial SPICE simulators [4-5]. The developed model well reproduces waveforms of the reverse-recovery charge, the recovery charge current and the total anode current simulated by the 2D-device simulator as shown in Figs. 4 and 5. It is important that the recovery charge current and the total anode current are almost equivalent as shown in Fig. 4b. Figs. 6 and 7 show the high-injection case of the recovery charge, the charge current and total anode current.

5. Conclusions

Reverse recovery effect of a P-i-N power diode is modeled for SPICE simulation by describing the dynamic carrier distribution in the N- drift layer. Nonquasi-static modeling technique is applied to describe the remaining carrier behavior. The developed model well reproduces 2D-device simulation results.

References