A Scalable POWER MOSFET Model with An Integrated Body-Diode Including Reverse Recovery

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ABSTRACT

For power MOSFET, the inherited parasitic source-bulk and drain-bulk diodes reverse recovery tail will increase the switching losses, stress other devices and give electro-magnetic-emission. Providing a power MOS model with integrated body-diode with reverse recovery capability will benefit a lot for power management circuit designers to predict the circuit performance such as power conversion efficiencies. Based on K.J.Tseng diode model, we present a scalable power MOSFET model with body-diode reverse recovery capability. The model parameters extraction flow, the simulation results for efficiencies in a boost-convert is given.

Keywords: power mosfet, body diode, reverse recovery, model, simulation

1 INTRODUCTION

Since its development in 1970s, the power MOSFET is used widely in low and medium voltage range power electronics circuit for its voltage control, fast switching speed, parallel connection implementation easiness. When power MOSFET is used as power switch, its inherited parasitic source-bulk and drain bulk diodes reverse recovery will increase the switching losses. This will limit the switching speed of the devices, lower the power conversion efficiency and complicated the thermal management system. The tail of the reverse recovery also put stress (both current and voltage has some non-zero values) on power MOSFET. So providing power MOSFET model with body diode reverse recovery capability will benefit the power management circuit designers for better performance prediction in some key design specification as power conversion efficiencies, safe-operating area definition.

Before the HiSim model becomes the industrial standard for HVMOS in 2008, the modeling of power MOSFET is basic macro model approach: the core MOSFET model is based on industrial standard BSIM plus sub circuit to take consideration of the parasitic resistance, diodes and capacitance which is not included in the BSIM models. The standard diode model incorporated in BSIM3/4 standard does not have reverse recovery so is not sufficient to describe the drain-body and source-body junctions in the power MOSFET. Our approach is replacing the internal diode model with external diode model which has reverse recovery capability. So the whole macro model of power MOSFET can predict accurate switching waveform for transistor level simulation.

Both physics and behavior diode models with reverse recovery capability is available. Based on the consideration of model implementation easiness in circuit simulator, integration friendliness into our MOSFET model itself, model parameter extraction simplicity, we choose the diode model by K.J.Tseng [1]. The diode model is easy to implement in any circuit simulator for it only uses liner elements, the parameters extraction is also straightforward. The model causes non-convergence problems based on our fully simulation test condition.

In this paper, first, we'll introduce the modeling approach of a diode with reverse recovery. Then the diode model parameter extraction results and the sub-circuit of our scalable power MOSFET model with body diode including reverse recovery capability are given. The simulation results on a real application circuit will show the benefit of the model.

2 DIODE MODEL WITH REVERSE RECOVERY

Diode is a minority carrier device. When the diode is turned off, the injected minority carriers when the diode is turned on need time to disappear by recombination or negative current flow. In order to predict the switching behavior of the diode, the model needs accurately describe the injected carrier distribution profile and also the time variance of the injected carrier distribution profile. For a device model in a circuit simulator, this is related to DC model which related terminal voltage to current though the device and dynamic model which predicts the time variance of the voltage and the current.

The DC behavior of the diode provided in Spice-simulator family is based on the Shockley equation (1):

$$I_D = I_{ss}(e^{qV_D/KT} - 1) \tag{1}$$

Plus the breakdown capability, this DC model of the diode is good enough for most of our application, and we have a mature flow of model parameters extraction flow based on measurement data.

The dynamic behavior of the diode in Spice model is based on charge storage effect. The charge storage components in a diode are depletion charge Q_d and injected carrier charge Q_j. The large signal diode model in Spice is shown in Fig. 1. [2]. The Ohmic resistance is not shown here for simplicity.

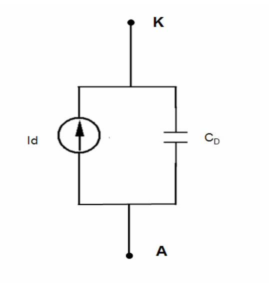

Fig. 1. Large signal diode model of SPICE2

The dynamic storage charge behavior is described by capacitance C_D. C_D is the depletion capacitor C_j in parallel with a high non-linear capacitance C_d which related to the injected carrier charge as described in equation (2). τ is the minority carrier life time:

$$C_d = \frac{dQ_d}{dV_D} = \tau\frac{dI_d}{dV_D} \tag{2}$$

How many minority carriers are injected when the diode is turned on? The relation between the injected carriers charge and current is described by the charge control equation (low level injection is assumed here):

$$I_D(t) = \frac{dQ_d}{dt} + \frac{Q_d}{\tau} \tag{3}$$

We assume the diode already reaches the static condition before turn it off, this means the time variance of injected carrier and current is zero. So the injected carrier charge is described by equation (4):

$$Q_d = I_D \times \tau = I_{ss}(e^{qV_D/KT} - 1)\times\tau \tag{4}$$

As mentioned before, the injected minority charges have two ways to disappear: by recombination and reverse current injections, this means it is related to loading condition and minority carrier life time.

So what is the minority carrier distribution in the diode and the time variance of this distribution during switching off?

The SPICE diode model treated the minority carriers as an instant function of applied voltage as seen in equation (4), when the diode voltage reaches negative, the Q_d disappears. This is the reason that the spice diode model cannot predict the correct reverse recovery shape especially after the voltage goes to negative [3].

There are several successful approaches for diode model with reverse recovery abilities. Cliff Ma and Laurence uses lumped-charge modeling technique to model power diodes, which P-I-N is the typical structure [4].

Our approach is based on the modeling approach of K.J.Tseng [1]. The concepts of their modeling are modification of the injected charge equation. Based on their study, dynamically, the injected charge is the function of the changing rate of the charge itself as described in this equation:

$$Q_d = I_d \times \tau - fs\frac{dQ_d}{dt} \tag{5}$$

fs is called softness factor which takes consideration of the spatial distribution of the injected carriers.

The modification of large signal diode model is shown in Fig. 2:

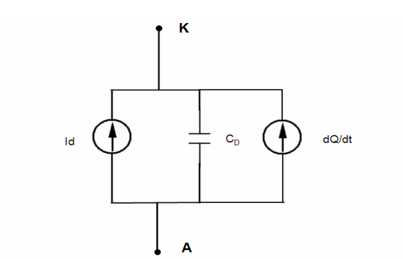

Fig. 2. Modified large signal diode model to have reverse recovery capability

So by paralleling another element which injects the dQ/dt components to the Spice diode model, the new diode model will have reverse recovery capability. Model implementation method is described in [5]. Only linear components are needed for the implementation and we use three model parameters to tune the reverse recovery curves: *fs*: softness factor, *tau*: transient time and *igain* which is added in our model for better reverse current peak tuning.

The advantage of the model is: model implementation simplicity and easiness integration the model into our existing models. For the reverse recovery parameter extraction is a separated flow, we still keep our model parameter extraction flow for the DC and the depletion capacitance C_j parameters.

3 POWER MOSFET MODEL WITH BODY DIODE INCLUDING REVERSE RECOVERY

The sub circuit of the scalable power MOSFET with body-diode has reverse recovery capability is shown as Fig. 3. By setting certain parameters of the MOSFET models, we can “turn off” the internal diode of the BSIM model, and then we replace internal BSIM diode with external reverse recovery sub circuit diode model.

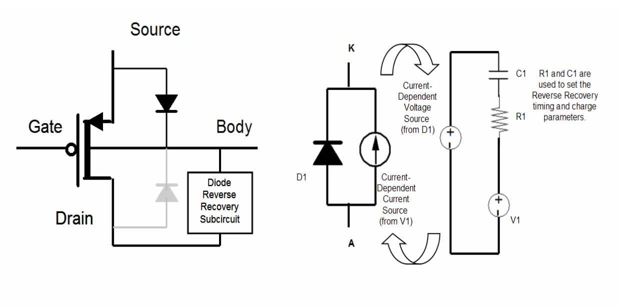

Fig. 3. Macro model of power MOSFET with body diode

Fig. 4 shows the simulation vs. measurement of reverse recovery waveform for a body diode of a certain size power transistor. The model predicts the DC, the switching transient waveform correctly.

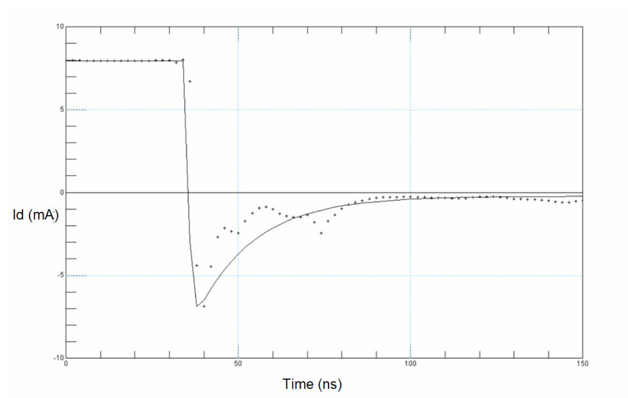

Fig. 4. Reverse recovery waveform of body diode for a power transistor

4 APPLICATION EXAMPLES: BOOST CONVERTER EFFICIENCIES

The boost converter is a circuit can convert a low DC voltage to a high DC voltage. The schematic of a typical boost converter is shown in Fig. 5. The ratio between output voltage and input voltage is called efficiency. Switching losses in the power transistors will make the efficiency high. And the inherited drain to body diode’s reverse recovery has a big effect on the efficiency.

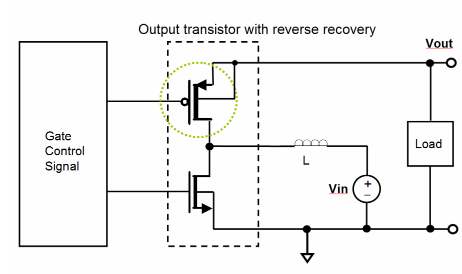

Fig. 5. Schematics of a boost converter

Fig. 6 (a) shows the simulated transistor current switching waveform with and without the reverse recovery for the drain to body diode. When turn off the transistor, the inherited drain to diode not only gives current spike to the device, also make the switching transient much longer. This costs the switching losses high and efficiency low. Fig. 6 (b) shows the output level difference between the two models with and without reverse recovery.

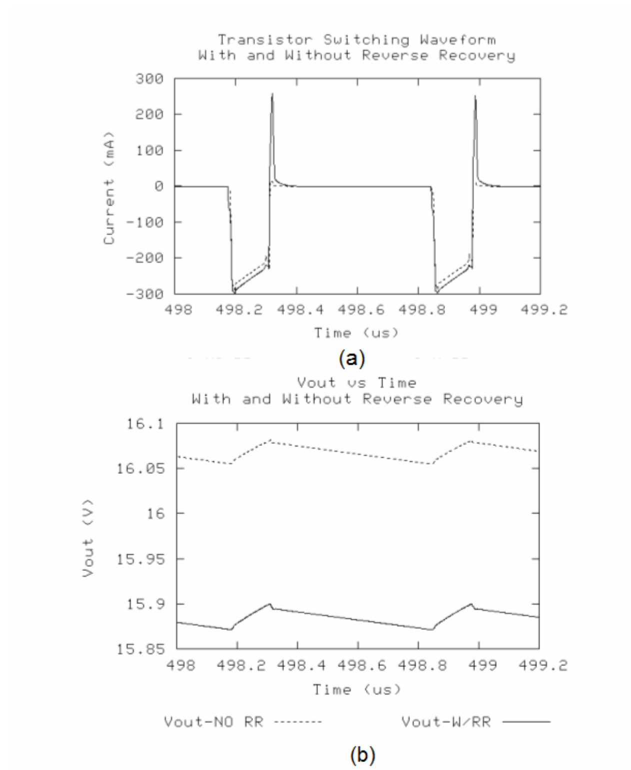

Fig. 6. (a) Simulated switching waveform of power transistor in boost converter

(b) Simulated output voltage waveform

CONCLUSION

In this paper, we presented a scalable power MOSFET models with integrated body diode with reverse recovery capability. The reason that normal diode model can not have correct reverse recovery shape is discussed. The modeling approach, model parameter extraction flow, simulation example in a boost converter is given.

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