High Accurate IGBT/IEGT Compact Modeling for Prediction of Power Efficiency and EMI Noise

Takeshi Mizoguchi, Yoko Sakiyama, Naoto Tsukamoto and Wataru Saito
Toshiba Electronic Devices & Storage Corporation, Saiwai-Ku, Kawasaki 212-8520, Japan
Email: takeshi3.mizoguchi@glb.toshiba.co.jp

Abstract—This paper presents a newly developed compact model of IGBT/IEGTs for prediction of power-loss and Electromagnetic-Interference (EMI) noise accurately. The proposed model focuses on the capacitance changes between each terminal during the switching operation and has two specific features, (1) the gate-emitter capacitance $C_{GE}$ formed by non-linear functions which consider the negative capacitance for reproducing the turn-on $dI/dt$ and (2) sub-circuits with ideal-diode and $CR$ connected to the gate-collector and the collector-emitter for reproducing the turn-off $dV/dt$ and the tail current. Compared to the conventional model, it was concluded that the proposed model is able to reproduce the measured turn-on and turn-off switching waveform accurately with high convergence.

Keywords—IGBT, IEGT, compact model, negative capacitance, tail current.

I. INTRODUCTION

Power semiconductor devices are the key components of various inverter and converter circuits for high power applications, such as voltage conversion and motor control. Recently, a model-based-design (MBD) is focused on automotive and power electronics systems. In order to realize the MBD process successfully, accurate circuit simulation is essential to predict the power efficiency and the EMI noise. A compact model that accurately describes the device characteristics is a prerequisite in order to predict the circuit performance [1].

For high power applications, the insulated gate bipolar transistor (IGBT) is one of the most important power semiconductor device which integrate MOS-gate control with bipolar conductivity modulation to achieve high input impedance and low on-resistance. The bipolar action originates the complex switching performance, although the conduction loss can be reduced. For example, the tail current is shown during the turn-off switching because of the remove of the stored carriers in the drift region. In the previous works, several IGBT compact models have been proposed [2]–[4]. However, the switching behaviors have not been reproduced sufficiently, especially, the turn-on behavior due to the negative capacitance. In addition, the convergence in a simulation is also problematic for the MBD process. This paper reports the newly developed compact model for IGBT/IEGTs that realizes the accurate prediction of not only the power-loss but also the EMI noise ($dI/dt$ and $dV/dt$) with high convergence. The evaluation of the developed model is done by verifying the power-loss, $dI/dt$ and $dV/dt$ of the inductive load switching circuit.

II. MODEL DESCRIPTIONS

A. Conventional model

The conventional IGBT model consists of a MOSFET part and a bipolar part as shown in Fig. 1 [5]. For the MOSFET part, a standard MOSFET model is used, for the bipolar part, however, a standard BJT model is not suitable, since it cannot correctly reproduce the switching characteristics due to high-level carrier injection and the non-quasi-static effects. Therefore the conventional model employs a special equivalent sub-circuit as shown in Fig. 1 (b) for the tail current behavior. The additional tail current source $G_t$ represents by the collector current $I(V_{sen})$ and the current source $G_{RBQ}$ as follows:

$$G_t = G_{RBQ} - I(V_{sen}) = \{C_{QB} \cdot V_q)/\tau_{aub} \} - I(V_{sen})$$ (1)

where the capacitor $C_{QB}$ is the charge storage element, and "$\tau_{aub}$" is the model parameter of the time-constant for the tail current.

B. Proposed model

Fig. 2 shows the proposed model structure of IGBT/IEGT devices in this work. The proposed model also consists of...
and simulation with the proposed model, respectively.

The proposed model has two specific features. One is the $C_{ge}$ formed by non-linear functions which consider the negative capacitance [6] for reproducing the turn-on $dV/dt$. Fig. 3 shows the comparison of the $C_{ge}$ characteristics between the conventional and the proposed models. $V_{ce}$ and $V_{ge}$ dependencies of the $C_{ge}$ by the conventional model are small. On the other hand, the proposed model considers the negative capacitance effect caused by the hole accumulation in the floating p-region of IEGTs. Consequently, the proposed model corresponds the $C_{ge}$ change during the switching and can adjust the turn-on $dI/dt$.

Another feature is sub-circuits with ideal-diode and $CR$ connected to the gate-collector and the collector-emitter for reproducing the turn-off $dV/dt$ and the tail current. The sub-circuit connected to gate-collector represents the effective gate-collector capacitance $C_{gc}$ during the turn-off switching and adjusts the turn-off $dV/dt$. Moreover two parallel sub-circuits connected to the collector-emitter represents the tail current due to these different time-constant values of the sub-circuits.

Furthermore, the proposed model has no current source which plays the tail current at the turn-off, and so the simulation convergence is superior compared to the conventional model. The simulation time by the proposed model for the inductive load switching is about 80 times shorter than that by the conventional model.

III. CIRCUIT SIMULATION RESULTS AND DISCUSSIONS

The model parameters were extracted from 4.5kV/1500A IEGT (Toshiba ST1500GXH24) characteristics. The model accuracy was evaluated by the inductive load switching characteristics (Input voltage $V_{in}=15V$, Supply voltage $V_{ce}=2800V$, Load inductor $L_{load}=100\mu H$ and Ambient temperature $T_{a}=125^\circ C$) considering with parasitic inductance in the measurement circuit. The free-wheel-diode (FWD) model [7] were chosen to validate the proposed model.

Fig. 4 shows the results for reproduction of measured static $I-V$ and $C-V$ characteristics after parameter extraction using both the conventional and the proposed models. All measured device characteristics are well reproduced.

Fig. 4. (a) $I_{ce}$-$V_{ce}$ characteristics at room temperature from $V_{ge}=7V$ to $V_{ge}=15V$. Symbols are measurements and lines are simulation results. And (b) Comparison of the modeled $C_{oes}/C_{oes}/C_{oes}$-$V_{ce}$ with measurements at room temperature at $V_{ge}=0V$. Symbols are measurements and lines are simulation results.

Fig. 5. Comparison of the measured and the simulated turn-on switching waveforms with the conventional model. Gate resistance $R_g=7.5\Omega$ and collector current $I_c=1500A$ are applied.

Fig. 5. Comparison of $V_{ce}$-$I_{ce}$ at $V_{ge}=0V$, $3000V$ and $C_{ge}$-$V_{ge}$ characteristics at $V_{ce}=0V$, $15V$ with conventional model and proposed model. Dashed and solid lines are simulation with the conventional model and simulation with the proposed model, respectively.
A. Turn-on switching characteristics

Fig. 5 shows a comparison of the measured and the simulated turn-on switching waveforms by the conventional model. Since the conventional model does not consider the negative capacitance caused by the hole accumulation around the gate and the floating p-region of IEGTs, the simulated d/dt value is much smaller than the measured one and the turn-on loss Eon is underestimated from the measured value. In contrast, the proposed model includes the negative capacitance function in the Cge model as shown in Fig. 3. Therefore it is possible to reproduce the measured turn-on switching waveform as shown in Fig. 6. Fig. 7 shows a comparison of error rate of the d/dt and the Eon with the conventional model and the proposed model. As a result, the error rates of the d/dt and the Eon are less than 4%, which is less than 1/20 of the error rate at the conventional model.

B. Turn-off switching characteristics

Fig. 8 shows a comparison of the measured and the simulated turn-off switching waveforms with the conventional model. Gate resistance Rg=7.5Ω and collector current Ice=1500A are applied. Reasonable values of the Cgc and the carrier lifetime parameter value have been considered by a bipolar action is not considered in the conventional model. Even in the conventional model, the turn-off switching waveforms can be reproduced by the increase of the Cgc value more than the measured static Cgc characteristic and the adjustment of the model parameter “Taub” for the tail current. Fig. 9 shows an adjustment result of the turn-off switching waveform by the conventional model, where the collector current Ice=1500A is applied. However, the accuracy is degraded at different current conditions. At the high collector current of Ice=2600A, the Eoff error rate is increased to about 10% due to gaps of the tail current and the dV/dt after the Vce overshoot as shown in Fig. 10.

In contrast, in the proposed model, the dV/dt has been fitted by the sub-circuit between the gate and the collector, and the tail current has been reproduced by two paralleled sub-circuits between the collector and the emitter. Even at the high collector current condition, the proposed model achieves very low error rate of less than 4% for both the dV/dt and the Eoff as shown in Figs. 11 and 12. This is because that the dV/dt after the Vce overshoot depend on the tail current waveform. Fig. 13 shows the simulated all current components at the turn-
off switching waveform in the proposed model, where the high collector current of 2600A is applied. The two paralleled sub-circuits between the collector and the emitter have different time-constant values and reproduce the tail current waveform accurately. Therefore the low error rate can be obtained by the proposed model even for different current conditions.

IV. CONCLUSION

We have developed the newly compact model of IGBT/IEGTs which includes the negative capacitance effect and sub-circuits with ideal-diodes and $CR$ for high accurate prediction of not only the power-loss but also EMI noise. The proposed model achieved to reproduce the switching characteristics in the inductive load. The error rate of the switching loss and d$V$/d$t$ for turn-on switching is 20 times smaller than the conventional model. The error rate of the turn-off switching characteristics was also reduced to less than 4% even for the various current condition. Furthermore, the simulation time of the proposed model is about 80 times faster than that of the conventional model. From these results, the proposed model is useful for high accurate prediction of power electronics circuit performances and MBDS.

References


