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

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***Abstract*—This paper presents a newly developed compact model of IGBT/IEGTs for prediction of power-loss and Electro-Magnetic-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 an 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_{RQB} as follows:

$$G_{\mathrm{t}} = G_{\mathrm{RQB}} - I(V_{\mathrm{sen}}) = \{(C_{\mathrm{QB}} \cdot V_{\mathrm{q}})/\mathrm{Taub}\} - I(V_{\mathrm{sen}}) \quad (1)$$

where the capacitor C_{QB} is the charge storage element, and "Taub" 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

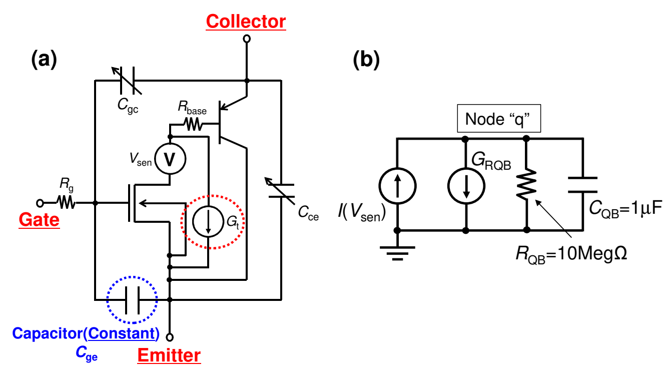

Fig. 1. (a) Conventional model structure of IGBT devices and (b) sub-circuit for the tail current calculation with the carrier lifetime.

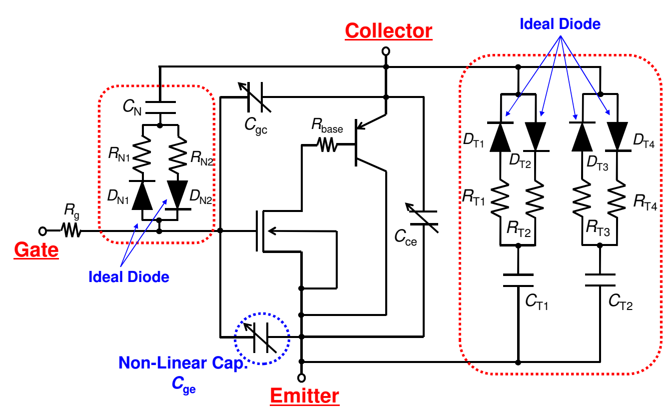

Fig. 2. Proposed model structure of IGBT/IEGT devices. The proposed model consists of a MOSFET part, a bipolar part, C_{ge} formed by non-linear functions and the sub-circuits with ideal-diode connected to the gate-collector and the collector-emitter.

a MOSFET part and a bipolar part. In order to the fair comparison of the conventional and the proposed models, model parameters of a MOSFET and a bipolar parts without the sub-circuits are shared each other in this work. The proposed model focuses on the capacitance changes between each terminal during the switching operation and the tail current during the turn-off switching.

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 $\mathrm{d}I/\mathrm{d}t$. 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 $\mathrm{d}I/\mathrm{d}t$.

Another feature is sub-circuits with ideal-diode and CR connected to the gate-collector and the collector-emitter for reproducing the turn-off $\mathrm{d}V/\mathrm{d}t$ 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 $\mathrm{d}V/\mathrm{d}t$. 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 not 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_{cc}=2800V, Load inductor L_{load}=100μH and Ambient temperature T_{a}=125°C) considering with parasitic inductance in the measurement circuit. The free-wheel-diode (FWD) model [7] were chosen to validate the proposed model.

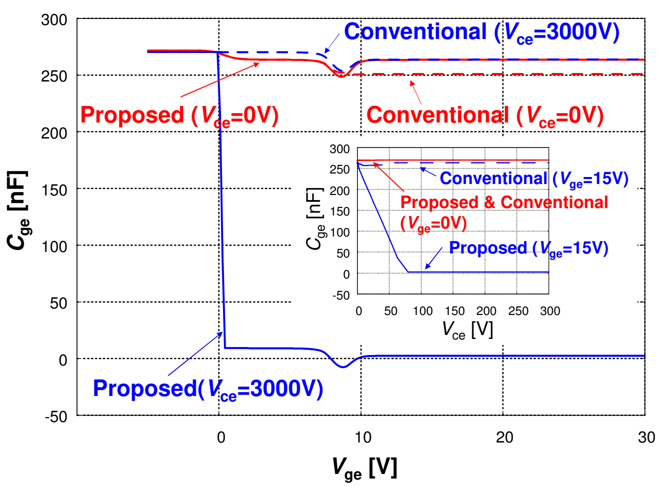

Fig. 3. Comparison of modeled C_{ge}-V_{ge} at V_{ce}=0V, 3000V and C_{ge}-V_{ce} characteristics at V_{ge}=0V, 15V with conventional model and proposed model. Dashed and solid lines are simulation with the conventional model and simulation with the proposed model, respectively.

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.

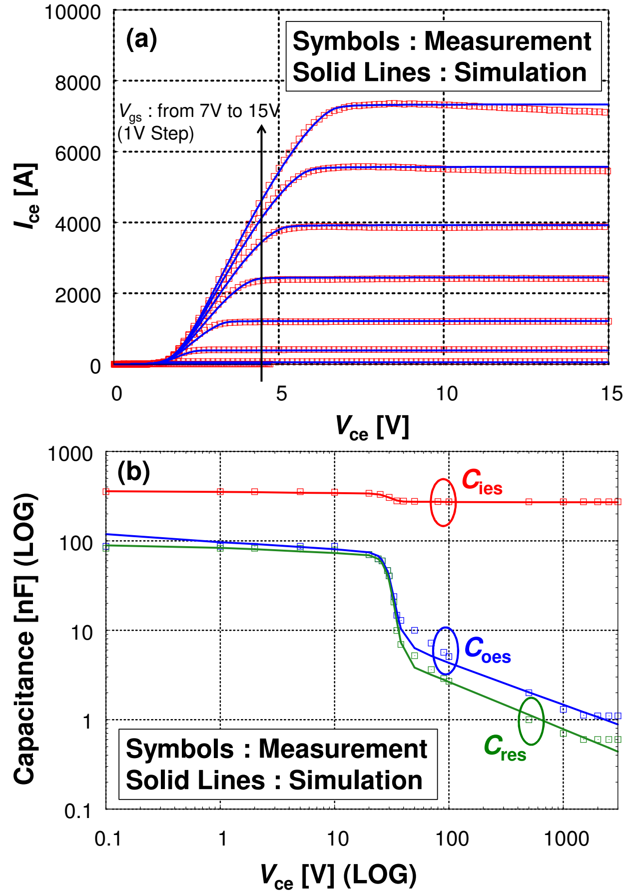

Fig. 4. (a) I_{ce}-V_{ce} characteristics at room temperature from V_{ge}=7V to V_{ge}=15V. Symbols are measurements and lines are simulation results. And (b) Comparison of the modeled C_{ies}/C_{oes}/C_{res}-V_{ce} with measurements at room temperature at V_{ge}=0V. Symbols are measurements and lines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

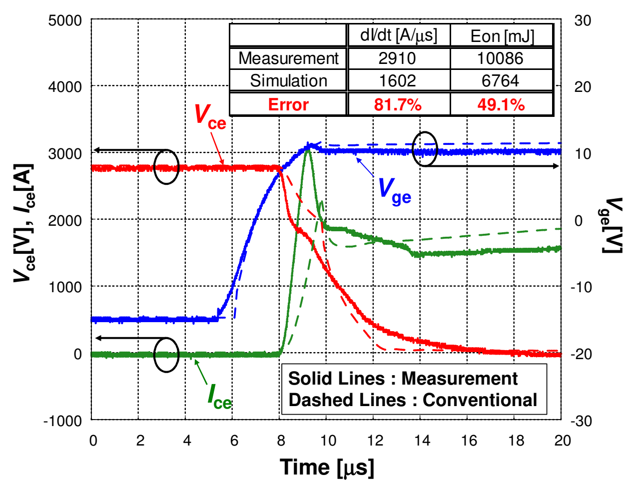

Fig. 5. Comparison of the measured and the simulated turn-on switching waveforms with the conventional model. Gate resistance R_{g}=7.5Ω and collector current I_{c}=1500A are applied.

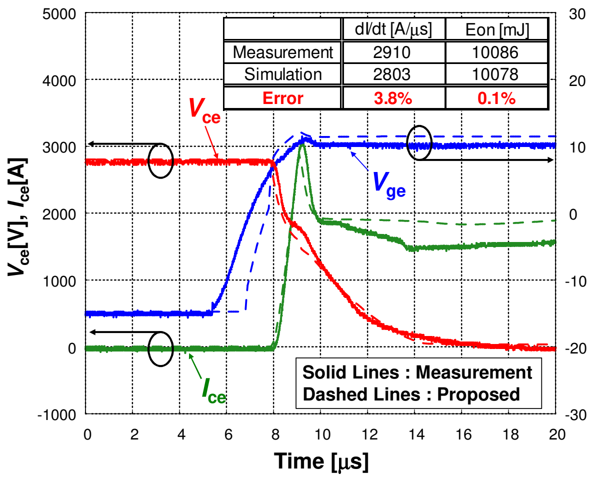

Fig. 6. Comparison of the measured and the simulated turn-on switching waveforms with the proposed model. Gate resistance R_g=7.5Ω and collector current I_c=1500A are applied.

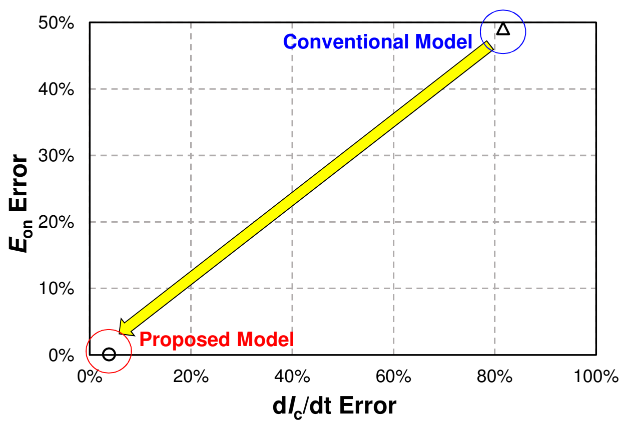

Fig. 7. Improvement of dI_c/dt and Eon error rate from the conventional model to the proposed models.

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 dI/dt value is much smaller than the measured one and the turn-on loss E_{on} is underestimated from the measured value. In contrast, the proposed model includes the negative capacitance function in the C_{ge} 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 dI/dt and the E_{on} with the conventional model and the proposed model. As a result, the error rates of the dI/dt and the E_{on} 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, where the collector current I_c=1500A is applied. The simulated dV/dt value by the conventional model is much higher than the measured one. Because increasing the effective capacitance due to the stored carriers in the drift region

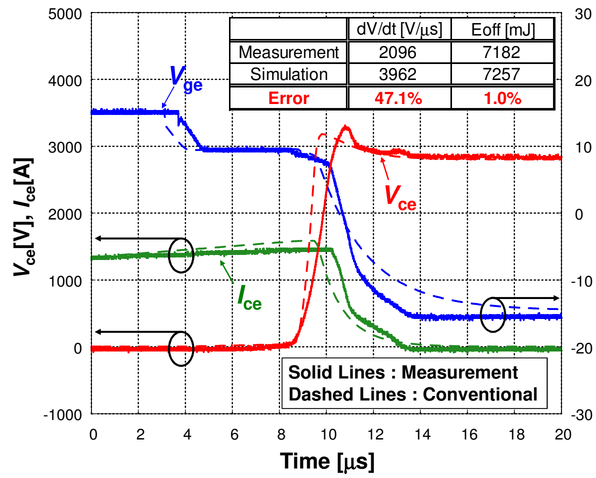

Fig. 8. Comparison of the measured and the simulated turn-off switching waveforms with the conventional model. Gate resistance R_g=7.5Ω and collector current I_c=1500A are applied.

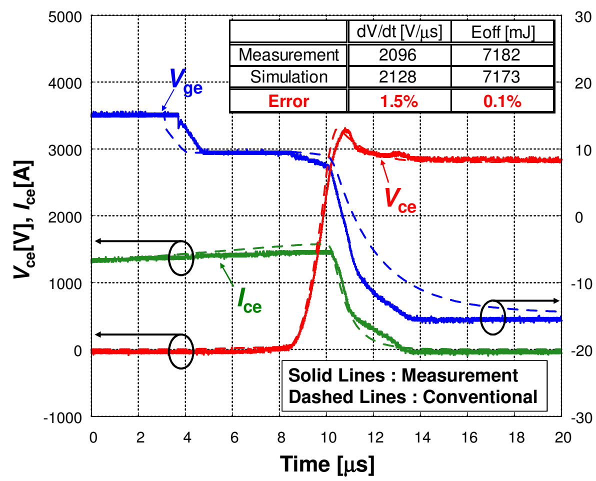

Fig. 9. Comparison of the measured and the simulated turn-off switching waveforms with the conventional model. Gate resistance R_g=7.5Ω and collector current I_c=1500A are applied. Reasonable values of the C_{gc} and the carrier lifetime parameter value have been considered.

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 C_{gc} value more than the measured static C_{gc} 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 I_c=1500A is applied. However, the accuracy is degraded at different current conditions. At the high collector current of I_c=2600A, the E_{off} error rate is increased to about 10% due to gaps of the tail current and the dV/dt after the V_{ce} 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 E_{off} as shown in Figs. 11 and 12. This is because that the dV/dt after the V_{ce} overshoot depend on the tail current waveform. Fig. 13 shows the simulated all current components at the turn-

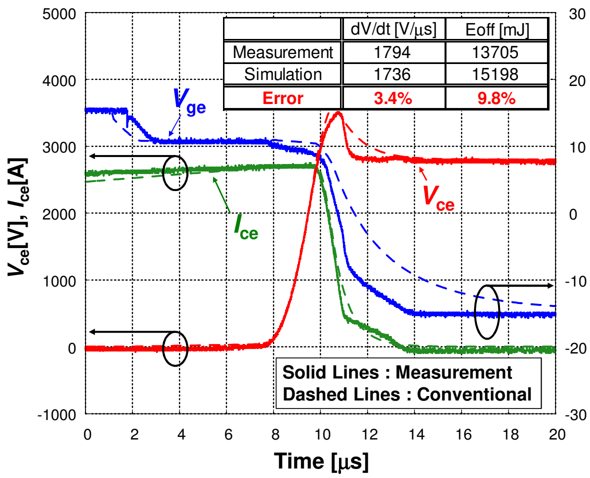

Fig. 10. Comparison of the measured and the simulated turn-off switching waveforms with the conventional model. Gate resistance R_g=7.5Ω and collector current I_c=2600A are applied.

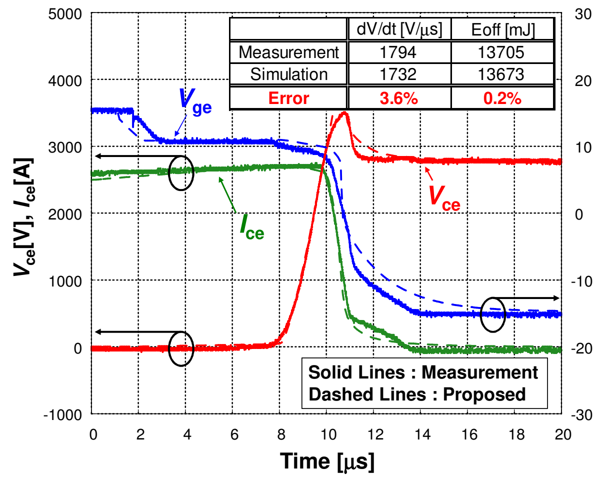

Fig. 12. Comparison of the measured and the simulated turn-off switching waveforms with the proposed model. Gate resistance R_g=7.5Ω and collector current I_c=2600A are applied.

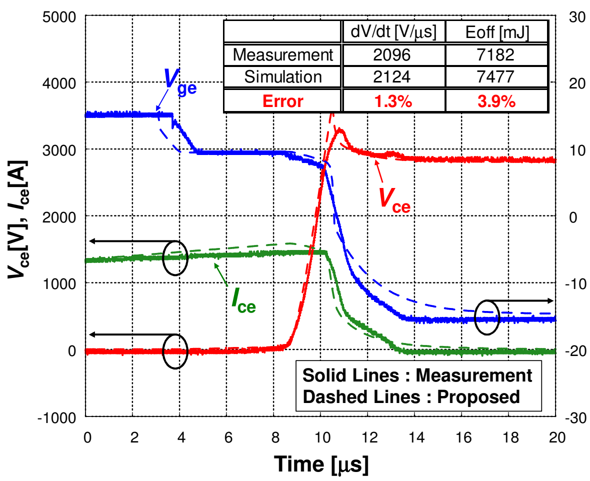

Fig. 11. Comparison of the measured and the simulated turn-off switching waveforms with the proposed model. Gate resistance R_g=7.5Ω and collector current I_c=1500A are applied.

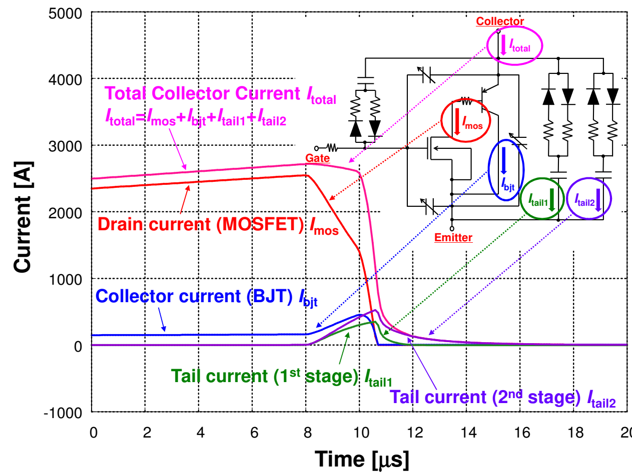

Fig. 13. The simulated all current components at the turn-off switching in the proposed model. Gate resistance R_g=7.5Ω and collector current I_c=2600A are applied.

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 dI/dt 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.

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