TOSHIBA

Technical Review

# IGBT Device Model Facilitating Highly Accurate Model-Based Development

**With the progressive introduction of model-based development (MBD) processes utilizing simulation technologies into a broad range of system design work in the fields of power electronics and in-vehicle electronics, there is a need for circuit simulations to predict power efficiency and electromagnetic interference (EMI) noise with a high degree of accuracy. In particular, a device model to precisely represent switching characteristics is essential for high-voltage and high-current insulated gate bipolar transistors (IGBTs), which are widely used in high-power applications including power control circuits.**

**Toshiba Electronic Devices & Storage Corporation is promoting the development of device models of its discrete semiconductor devices for MBD. We have now developed an IGBT device model taking into consideration the dynamic flow of both electrons and holes in switching operations as a replacement for conventional models, in which the tradeoff between power efficiency and EMI noise prediction is a serious issue. We have confirmed that the new model achieves highly accurate reproduction of switching characteristics measured by an actual circuit with high convergence.**

## 1. Introduction

In recent years, MBD has been attracting plenty of attention as a means of system design in the fields of power and automotive electronics. With MBD, appropriate models are created in each phase of the system development cycle to facilitate semiconductor-, circuit-, and system-level simulations. MBD helps to reduce the development cycle and prototyping iterations considerably.

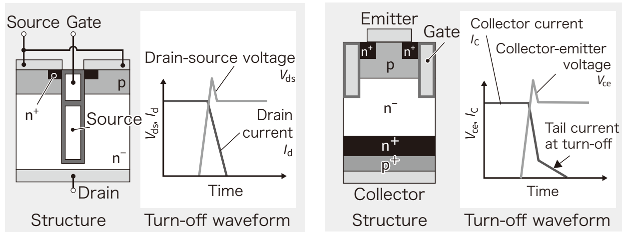
For the development of semiconductor devices, circuit simulators typified by the Simulation Program with Integrated Circuit Emphasis (SPICE) are utilized to predict circuit performance. Circuit simulators incorporate physical device models (i.e., approximate equations) that represent complicated electrical characteristics of semiconductor devices. The characteristics of each device are expressed as parameters of these equations. Device models and their parameters provide an interface between circuit design and device development.

To facilitate MBD, it is necessary to accurately predict the power efficiency of the circuits to be incorporated into a system and the EMI noise generated by each semiconductor device. Therefore, models that accurately represent device characteristics are also required for power semiconductor devices to be used in a circuit. Power semiconductor devices, which are mainly used in inverter and converter circuits, are essential for power conversion and motor control. It was difficult, however, for a circuit simulator to accurately predict both the power efficiency and EMI noise of IGBTs for high-current, high-voltage control applications.

To solve this problem, Toshiba Electronic Devices & Storage Corporation has developed a new IGBT device model, taking into consideration the dynamic flow of both electrons and holes in bipolar switching operation. The newly developed IGBT device model makes it possible to predict not only power loss but also the changing rates of collector voltage (*dV/dt*) and collector current (*dI/dt*) over time. This report provides an overview of this IGBT device model.

# 2. IGBT device models

**Figure 1** compares the structures and turn-off waveforms of the vertical metal-oxide-semiconductor field-effect transistor (MOSFET), a type of unipolar device, and the vertical IGBT, a type of bipolar device. Since an IGBT is a type of bipolar device that uses both electrons and holes as charge carriers, its collector current ($I_C$) does not disappear immediately at turn-off but only once all charge carriers accumulated in a device have recombined. These carriers yield a characteristic tail current at turn-off.




(a) Vertical MOSFET (unipolar device)

(b) Vertical IGBT (bipolar device)

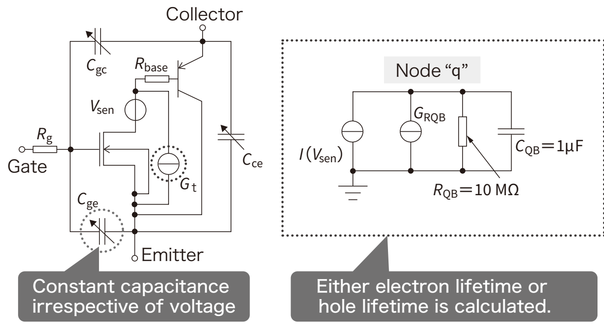
n : n-type semiconductor
n⁺ : heavily doped n-type semiconductor
n⁻ : lightly doped n-type semiconductor
p : p-type semiconductor
p⁺ : heavily doped p-type semiconductor

**Figure 1. Differences in structure and turn-off waveforms of unipolar and bipolar devices**

In the case of the IGBT, a type of bipolar device, the tail current that occurs at turn-off is one of the factors that cause an increase in switching loss.

## 2.1 Conventional IGBT device model

**Figure 2** shows the conventional IGBT device model that was commonly used previously[1]. An IGBT is composed of a MOSFET and a pnp transistor (p: p-type semiconductor, n: n-type semiconductor). The conventional IGBT device model shown in **Figure 2**(a) uses a standard bipolar junction transistor (BJT) model. Since this BJT model does not include carrier lifetime, it cannot express complicated switching behavior specific to an IGBT. To compensate for this inability, the conventional IGBT device model uses a special sub-circuit model specifically designed to represent turn-off tail current. This sub-circuit model has a current source of $I$ ($V_{sen}$) that represents tail current as an additional current that flows through the core MOSFET ($G_t$), considering carrier lifetime.




(a) Conventional IGBT device model

(b) Sub-circuit for calculation of tail current

$C_{gc}$ : gate-collector capacitance
$R_{base}$ : base resistance
$C_{ce}$ : collector-emitter capacitance
$R_{QB}$ : resistance for calculationstability
$C_{ge}$ : gate-emitter capacitance
$R_g$ : gate resistance
$V_{sen}$ : voltage source for current monitor
$G_{RQB}$ : current source for calculation of tail current
$C_{QB}$ : capacitance for calculation of tail current

**Figure 2. Conventional IGBT device model and sub-circuit for calculation of tail current considering carrier lifetime**

An IGBT is composed of a MOSFET and a pnp transistor. The current I ($V_{sen}$) calculated by the sub-circuit is added as $G_t$ at turn-off.

## 2.2 Newly developed IGBT device model

**Figure 3** shows the newly developed IGBT device model, which has two features. First, in order to represent *dI/dt* at turn-on, the new model expresses the gate-emitter capacitance ($C_{ge}$) with a nonlinear function, taking negative capacitance into consideration [2].

**Figure 4** compares the $C_{ge}$ characteristics of the conventional and newly developed IGBT device models. In the conventional model, $C_{ge}$ is hardly dependent on the gate-emitter voltage ($V_{ge}$) and collector-emitter voltage ($V_{ce}$). However, since the new model takes into consideration the negative capacitance effect due to the holes accumulated in the floating p-type region, $C_{ge}$ changes according to the changes in $V_{ge}$ and $V_{ce}$ during switching. Therefore, the new model allows turn-on *dI/dt* to be adjusted. The second feature of the new model is that it has switching sub-circuits between the gate and the collector and between the collector and the emitter of an IGBT. The sub-circuits are composed of ideal diodes, resistors, and capacitors to express

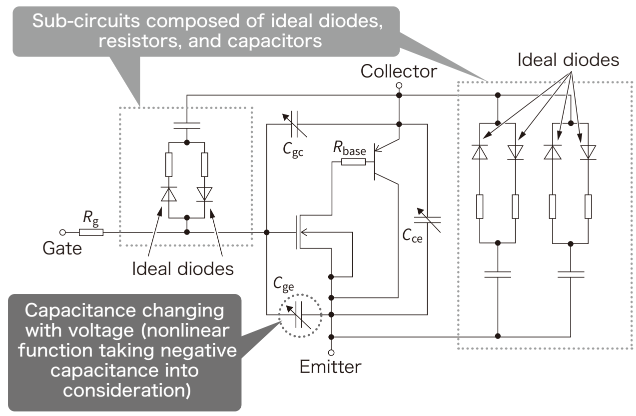



**Figure 3. Newly developed IGBT device model**

To compare the performance of the newly developed and conventional models, they are given the same parameters for the portions that express the DC and capacitance characteristics.

$dV/dt$ and tail current at turn-off. The sub-circuit between the gate and the collector expresses an effective change in gate-collector capacitance ($C_{gc}$) at turn-off, allowing turn-off $dV/dt$ to be adjusted. The two sub-circuits connected in parallel between the collector and the emitter represent different lifetimes for electrons and holes in a bipolar IGBT, thereby expressing tail current at turn-off. Furthermore, since the new model does not use a current source to express turn-off tail current, the new model provides better calculation convergence than the conventional model. We simulated a simple inductive load switching circuit using the newly developed and conventional device models. The new model increased the simulation speed by a factor of approximately 80(*1) compared to the conventional model that required a simulation run-time of 53.24 seconds.

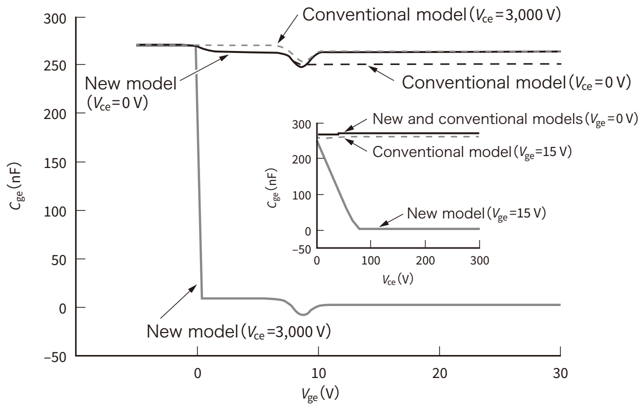



**Figure 4. Comparison of gate-emitter capacitance ($C_{ge}$) characteristics of conventional and newly developed IGBT device models**

The new model expresses negative capacitance with a nonlinear function, allowing its dependence on voltage to be adjusted with parameters of the function.

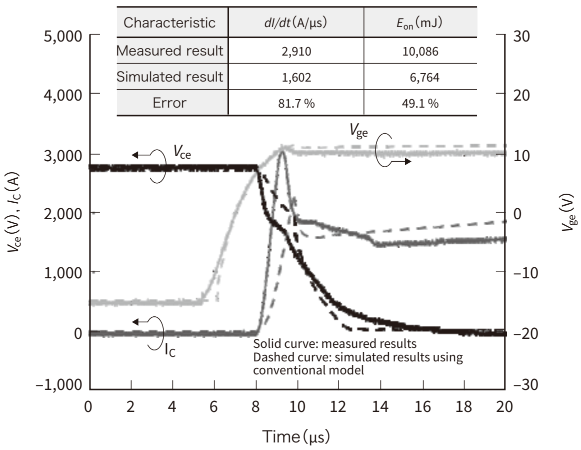
## 3. Circuit analysis

To verify the adequacy of the new device model, we performed an evaluation to determine whether it successfully replicates the switching characteristics of an inductive load switching circuit, using the ST1500GXH24 4.5 kV/1 500 A injection-enhanced gate transistor (IEGT). For this evaluation, we utilized a model of a freewheeling diode that takes its bipolar behavior into consideration(3).

### 3.1 Turn-on characteristics

**Figure 5** compares the measured turn-on switching waveforms with those simulated using the conventional IGBT device model. The conventional model does not take into consideration the negative capacitance of the holes accumulated in the gate and the floating p-type layer. Therefore, the simulated $dI/dt$ is substantially lower than the measured $dI/dt$, causing the loss of the freewheeling diode ($E_{rr}$) to be extremely small. Consequently, the simulated turn-on loss ($E_{on}$) was estimated to be excessively lower than the measured $E_{on}$.

Next, **Figure 6** compares the measured turn-on switching waveforms with those simulated using the new IGBT device model. The new model can replicate the measured turn-on characteristics with high accuracy by taking negative capacitance into consideration as a $C_{ge}$ model. **Figure 7** compares the error of the turn-on $dI/dt$ and the $E_{on}$ values simulated using the newly developed and conventional models with respect to the measured results. The new model simulated $dI/dt$ with an error of 3.8%, more than 95% lower than the error obtained from the conventional model.

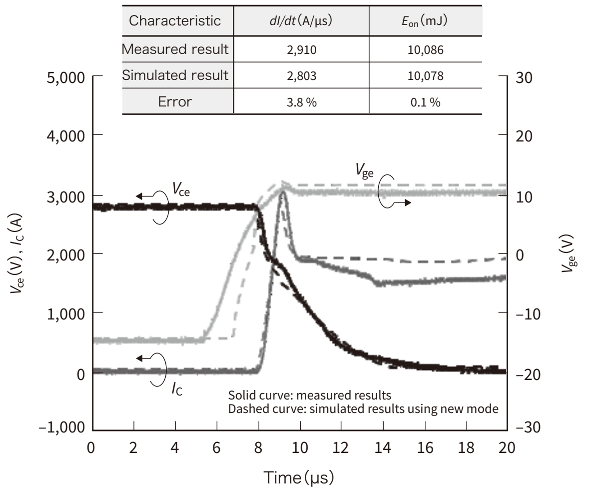



| Characteristic | $dI/dt$ (A/μs) | $E_{on}$ (mJ) |
|---|---|---|
| Measured result | 2,910 | 10,086 |
| Simulated result | 1,602 | 6,764 |
| Error | 81.7 % | 49.1 % |

**Figure 5. Comparison of measured turn-on switching waveforms and those simulated using conventional IGBT device model**

The conventional model does not take negative capacitance into consideration. A large effective capacitance causes the slope of the simulated $I_C$ curve during switching to be shallower than the measured $I_C$ curve.

(*1) As of May 2019 as surveyed by Toshiba Electronic Devices & Storage Corporation in comparison with a circuit model composed of a current source, resistors, and capacitors under the following conditions: resistor = 7.5 Ω, current = 1 500 A, temperature = 125°C




| Characteristic | $dI/dt$ (A/μs) | $E_{on}$ (mJ) |
|---|---|---|
| Measured result | 2,910 | 10,086 |
| Simulated result | 2,803 | 10,078 |
| Error | 3.8 % | 0.1 % |

**Figure 6. Comparison of measured turn-on switching waveforms and those simulated using newly developed IGBT device model**

The new model takes negative capacitance into consideration with respect to $C_{ge}$, making it possible to replicate turn-on characteristics with high accuracy.

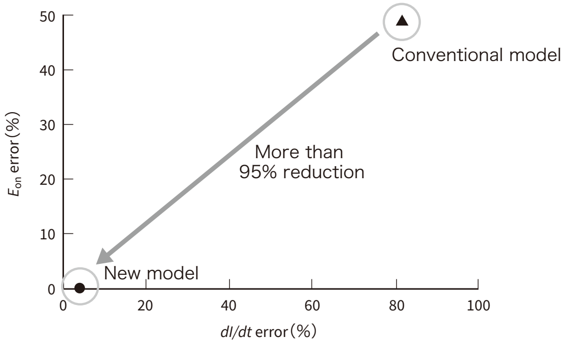


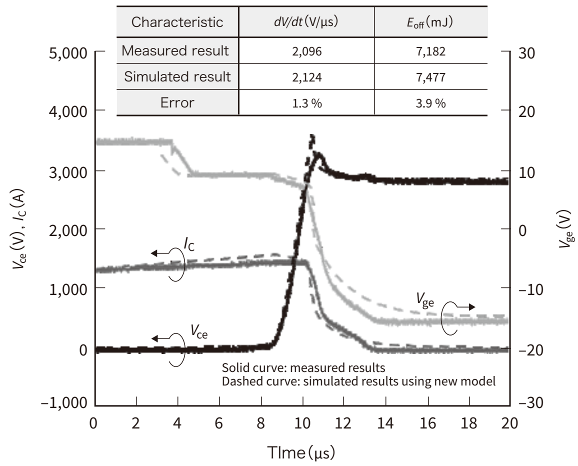

**Figure 7. Improvement of error rates of collector current change rate and turn-on loss simulated by newly developed IGBT device model compared with those simulated by conventional model**

The new model replicates turn-on characteristics with considerably higher accuracy than the conventional model.

## 3.2 Turn-off characteristics

Since the conventional model represents tail current by considering carrier lifetime, it replicates turn-off characteristics with high accuracy in the low-$I_C$ region. It is difficult, however, to accurately represent tail current in the high-$I_C$ region without compromising the accuracy of $dI/dt$ and $dV/dt$ at turn-off since the tail current model has little effect on the high-$I_C$ region.

**Figure 8** compares the measured turn-off characteristics with those simulated using the newly developed model at the rated $I_C$ of 1500 A. With the new model, the switching sub-circuit connected between the gate and the collector makes it possible to adjust turn-off $dV/dt$ while maintaining the accuracy of static $C_{gc}$ characteristics. In addition, the two switching sub-circuits connected in parallel between the collector and the emitter can represent tail current at turn-off. On the other hand, with the conventional model, the turn-off loss ($E_{off}$) and the turn-off $dV/dt$ have a trade-off relationship as shown in **Figure 9**. Consequently, the new model does not have this trade-off, representing both these characteristics with an error of less than 4%.




| Characteristic | $dV/dt$ (V/μs) | $E_{off}$ (mJ) |
|---|---|---|
| Measured result | 2,096 | 7,182 |
| Simulated result | 2,124 | 7,477 |
| Error | 1.3 % | 3.9 % |

**Figure 8. Comparison of measured turn-off switching waveforms and those simulated using newly developed IGBT device model**

The sub-circuits connected between the gate and the collector and between the collector and the emitter make it possible for the new model to replicate turn-off waveforms with high accuracy.

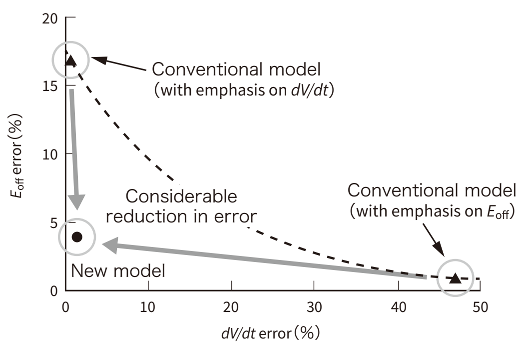



**Figure 9. Improvement of error rates of collector voltage change rate and turn-off loss simulated by newly developed IGBT device model compared with those simulated by conventional model**

The conventional model has a trade-off between $E_{off}$ and turn-off $dV/dt$. The new model overcame this trade-off, replicating $E_{off}$ and $dV/dt$with high accuracy.

# 4. Conclusion

We have developed a new IGBT device model that has switching sub-circuits between the gate and the collector and between the collector and the emitter. These sub-circuits are composed of ideal diodes, resistors, and capacitors, taking negative capacitance into consideration with respect to $C_{ge}$. We confirmed that this device model replicates the measured characteristics of an inductive load switching circuit. Compared with the conventional model, the new model reduces the simulation error for turn-on *dI/dt* by more than 95%. The new model also overcame the trade-off between $E_{off}$ and *dV/dt* at turn-off, achieving an $E_{off}$ error of less than 4%. Furthermore, the new model increases the simulation speed by a factor of roughly 80, compared with the conventional model that uses a current source to represent tail current. Therefore, the new model can be extensively used for the prediction of circuit characteristics and MBD in the field of power electronics.

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## References

(1) Kraus, R. et al. 2018. "Physics-based models of power semiconductor devices for the circuit simulator SPICE". PESC 98 Record 29th Annual IEEE Power Electronics Specialists Conference. Fukuoka, 1998-05, IEEE. 2018: 1726–1731.

(2) Yamaguchi, M. et al. 2004. "IEGT design criterion for reducing EMI noise". Proceedings of the 16th International Symposium on Power Semiconductor Devices and ICs (ISPSD '4). Kitakyushu, 2004-05, IEEE. 2004: 115–118.

(3) Dastfan, A. 2007. "A New Macro-Model for Power Diodes Reverse Recovery". Proceedings of the 7th WSEAS International Conference on Power Systems. Beijing, China, 2007-07, World Scientific and Engineering Academy and Society (WSEAS). 2007: 48–52.