Compact Modeling of the Punch-Through Effect in SiC-IGBT for 6.6kV Switching Operation with Improved Performance

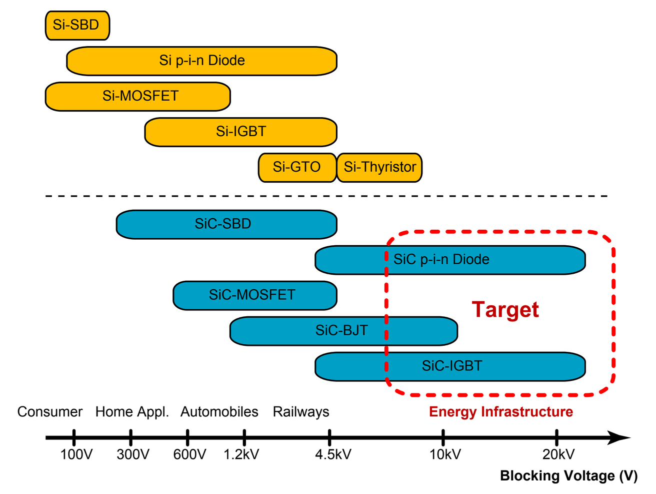
HIROSHIMA UNIVERSITY

Masataka Miyake, Fumiya Ueno, Dondee Navarro and Mitiko Miura-Mattausch

SILVACO

Motivation

- For over 5kV & 100A/cm² operations at a few hundred Hz switching frequency, SiC IGBTs have the lowest on-state voltage among state-of-the-art high-voltage power semiconductor devices such as silicon light-triggered thyristors [1].



- Accurate and stable compact model of SiC IGBTs for circuit simulation is required for circuit designers to efficiently design/optimize circuitry of power converters.

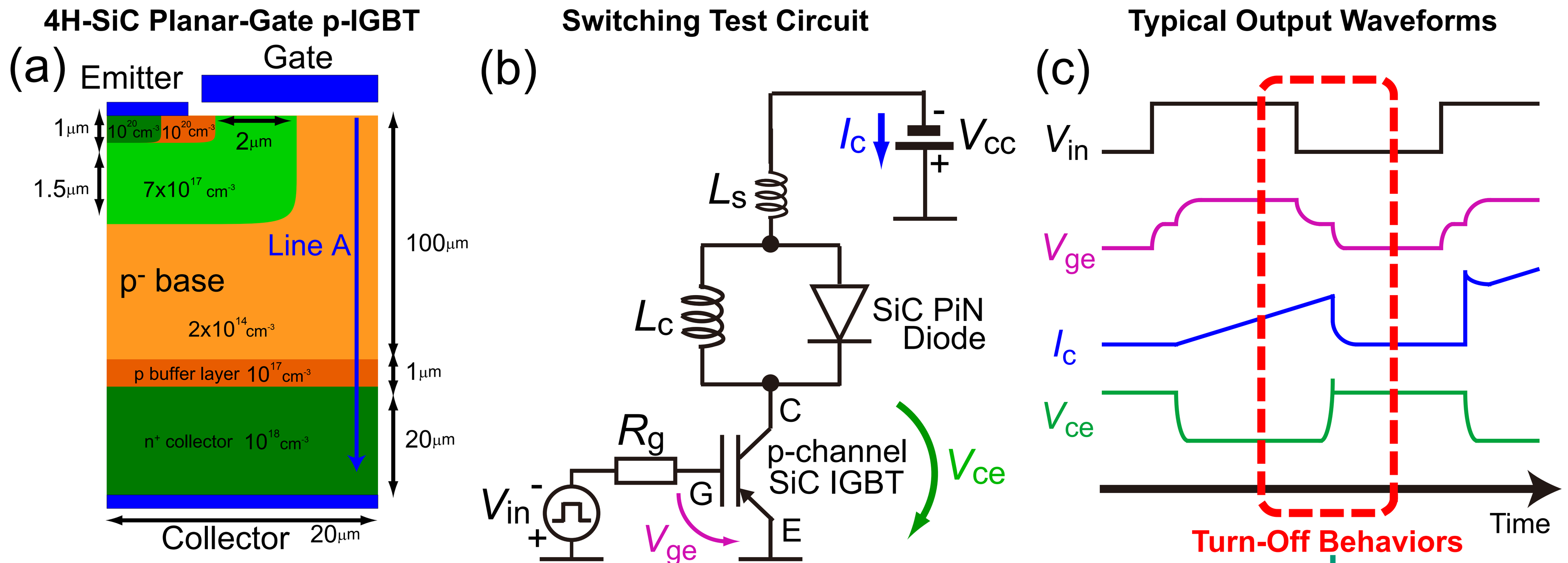
Benefits from the good compact model
1. Higher conversion efficiency
2. Reduction of cost
3. Less turn-around time

	Silicon	4H-SiC
E_g (eV)	1.1	3.26
n_i (cm^{-3})	1.45×10^{10}	9.7×10^{-9}
E_c (V/cm)	0.3×10^{6}	2×10^{6}
ϵ_r (-)	11.8	10

[1] FIRST-SiC, http://www.first-sic.jp/tec/04/

Simulation Setup

4H-SiC Planar-Gate p-IGBT | Switching Test Circuit | Typical Output Waveforms

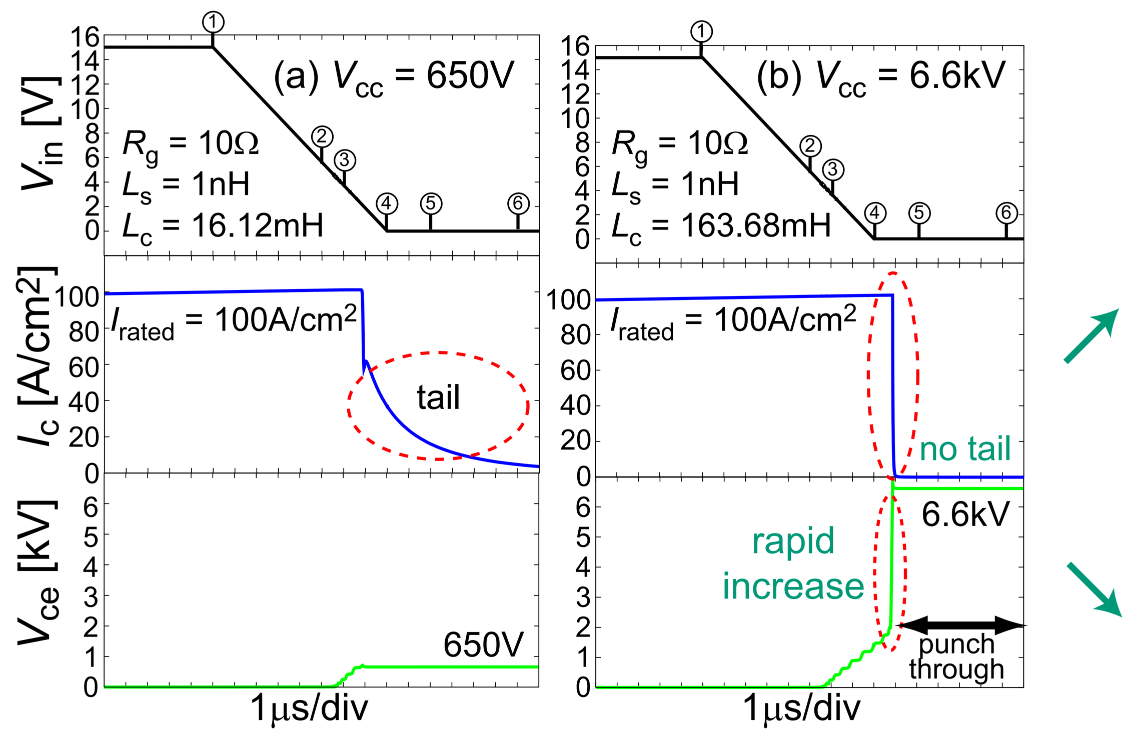


Focused in this work.

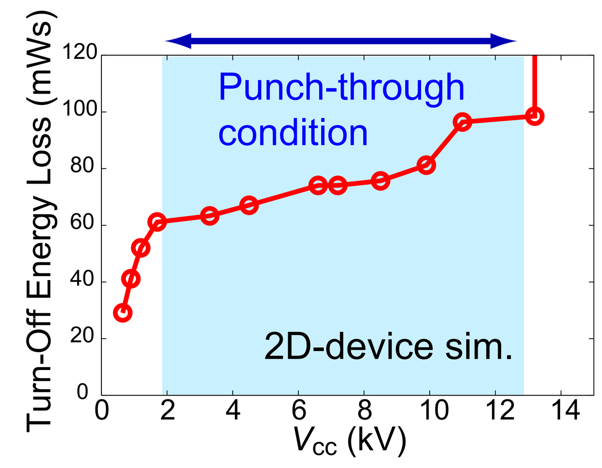
Investigation with 2D-Device Simulation

2D-device simulation is performed using ATLAS by Silvaco.

T_f=8µs Turn-Off Behaviors



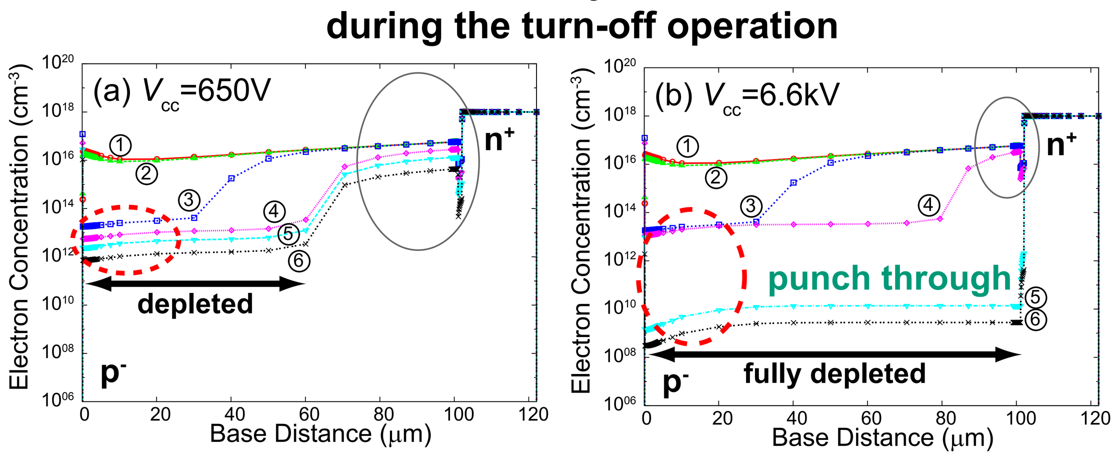
normal base resistance | extremely high base resistance



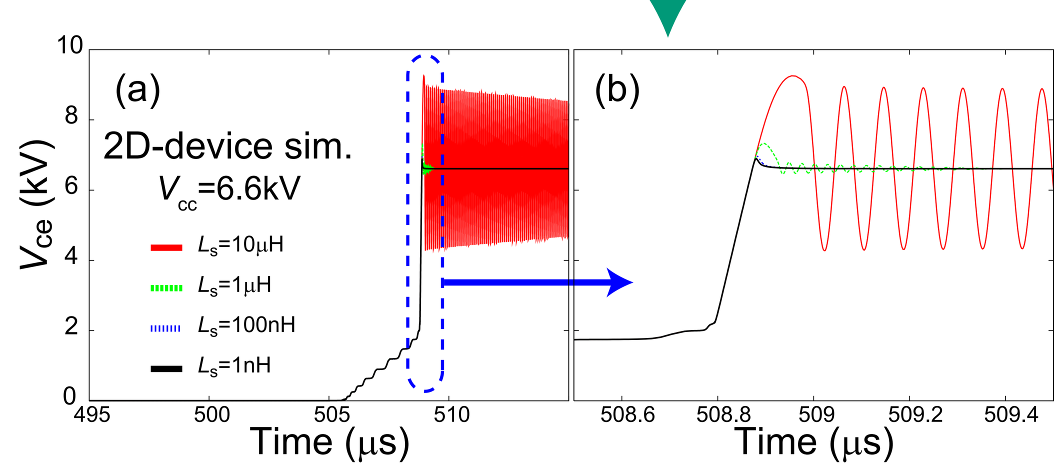
Absence of the tail current results in very low energy loss.

V_{ce} rapidly increases immediately after the punch through (PT) occurs.

Electron density distributions during the turn-off operation



carriers still left in the base | almost no base carriers



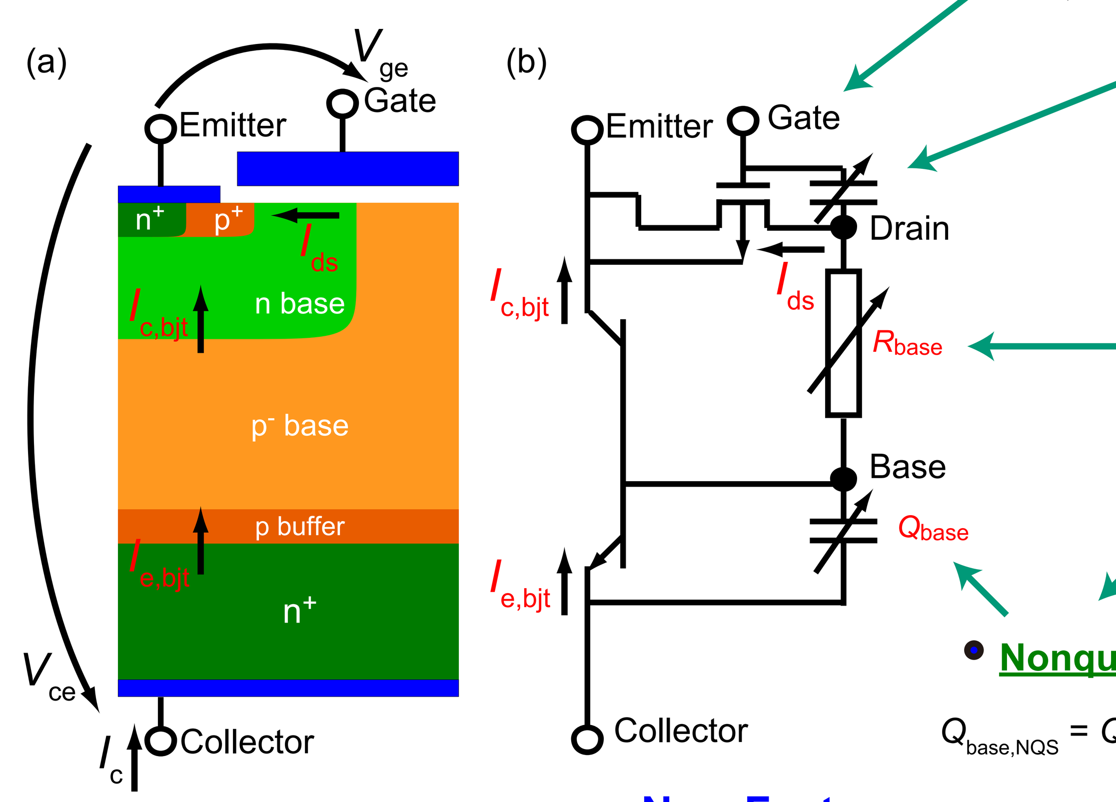
Rapid increase of V_{ce} causes a large voltage overshoot which can trigger a ringing phenomenon if a parasitic stray inductance L_s is relatively large.

To exploit the advantage in the turn-off energy loss while at the same time avoid the ringing, the punch-through (PT) effect must be modeled accurately.

Compact Model HiSIM-IGBT

HiSIM-IGBT is a unified Si/SiC IGBT model for circuit simulation.

For example, a planar-gate p-IGBT below is conceptually represented with the common equivalent circuit beside.



- Surface-Potential-Based MOSFET Model

$$-Q_s = C_{ox}(V_G' - \varphi_S(y))$$
$$= \sqrt{\frac{2\varepsilon_{Si}qN_{sub}}{\beta}}\left\{e^{-\beta\varphi_S(y)} + \beta\varphi_S(y) - 1 + \frac{n_{p0}}{p_{p0}}\left[e^{\beta(\varphi_S(y)-\varphi_f(y))} - e^{-\beta\varphi_f(y)}\right]\right\}^{1/2}$$

- Surface-Potential-Based MOS Capacitor Model

$$Q_{S,ov} = C_{ox}(-V'_{G,ov} + \varphi_{S,ov})$$
$$= \sqrt{\frac{2\varepsilon_{Si}qN_{base}}{\beta}}\left\{e^{+\beta\varphi_{S,ov}} - \beta\varphi_{S,ov} - 1 + \frac{n_{p0}}{p_{p0}}\left[e^{-\beta\varphi_{S,ov}} - 1\right]\right\}^{1/2}$$

- Base/JFET Resistance Model

$$R_{base} = \frac{1}{qA(\mu_n + \mu_p)}\int_0^{W_{base}} \frac{1}{p_{excess}(y)}dy$$

- Excess Base Charge Model

$$Q_{base} = qA\int_0^{W_{base}} p_{excess}(y)dy$$

- Nonquasi-Static Carrier Behavior Model

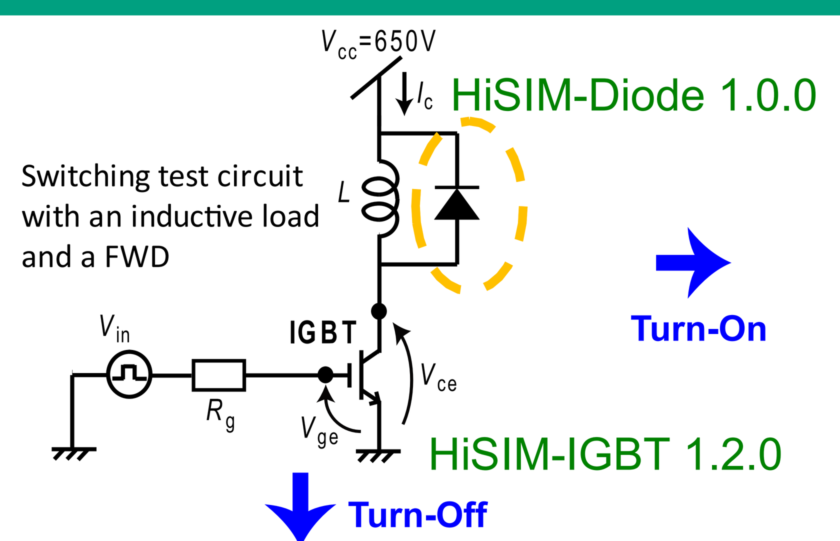
$$Q_{base,NQS} = Q_{base,NQS,prev} + \frac{\Delta t}{\tau_{tail} + \Delta t}(Q_{base} - Q_{base,NQS,prev})$$

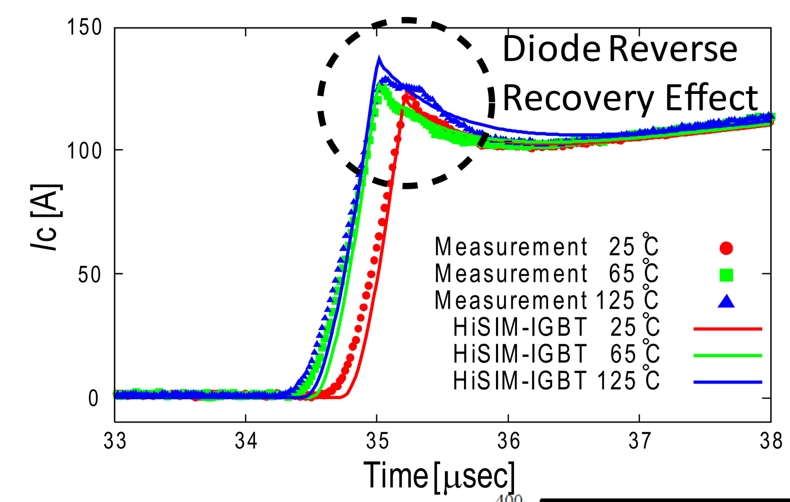
New Features:
- Carrier Distribution Model Considering the PT Effect
- Depletion Width Model Considering the PT Effect and the Carrier Increase Due to the Velocity Saturation

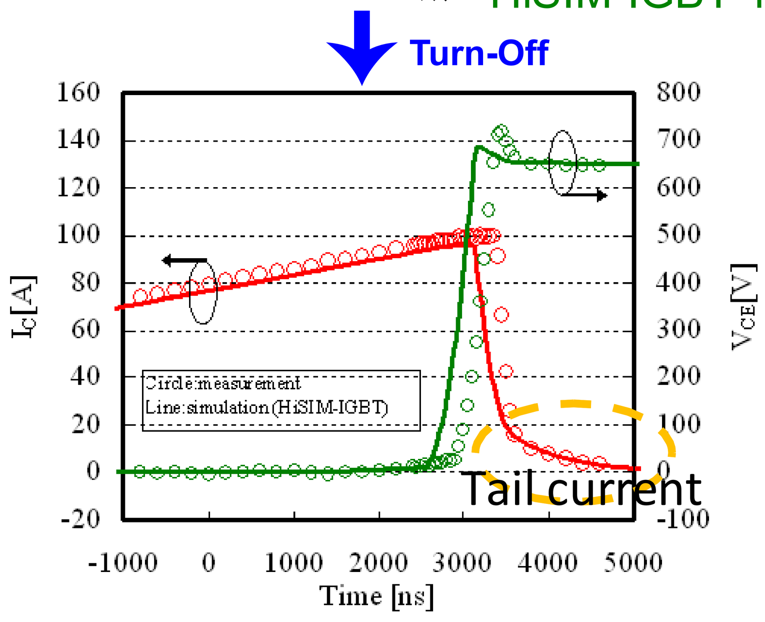
HiSIM-IGBT [2,3] developed for Si IGBTs has been extended by adapting material parameters to 4H-SiC and by including new features for the PT effect.

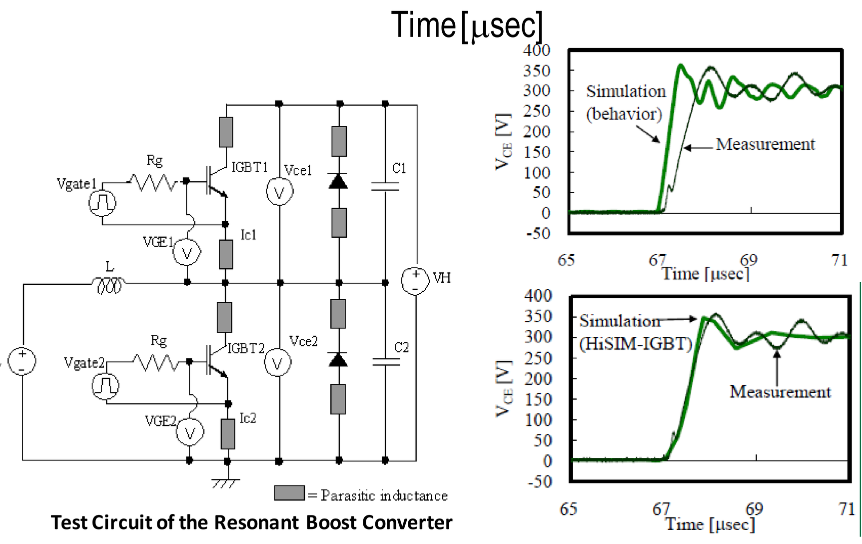
[2] M. Hirose, K. Shizuku, M. Miyake, M. Miura-Mattausch, H. J. Mattausch, and U. Feldmann, "Development of the HiSIM-IGBT Model for EV/HV Electric Circuit Simulation," in Proc. the 1st Int'l Electric Vehicle Tech. Conf. (EVTeC), Yokohama, May 2011.
[3] M. Miyake, M. Ueno, J. Nakashima, H. Masuoka, U. Feldmann, H. J. Mattausch, M. Miura-Mattausch, T. Ogawa, T. Ueta, "Temperature Dependence of Switching Performance in IGBT Circuits and its Compact Modeling," in Proc. ISPSD, pp. 148-151, San Diego, May 2011.

Achievements of HiSIM-IGBT for Silicon Data







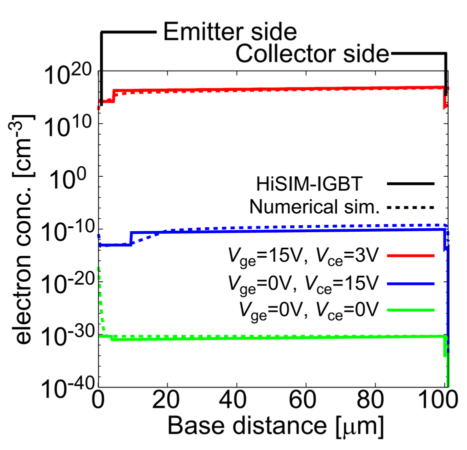


PWM power converter simulation is stably converged and the result well reproduces the measurement data.

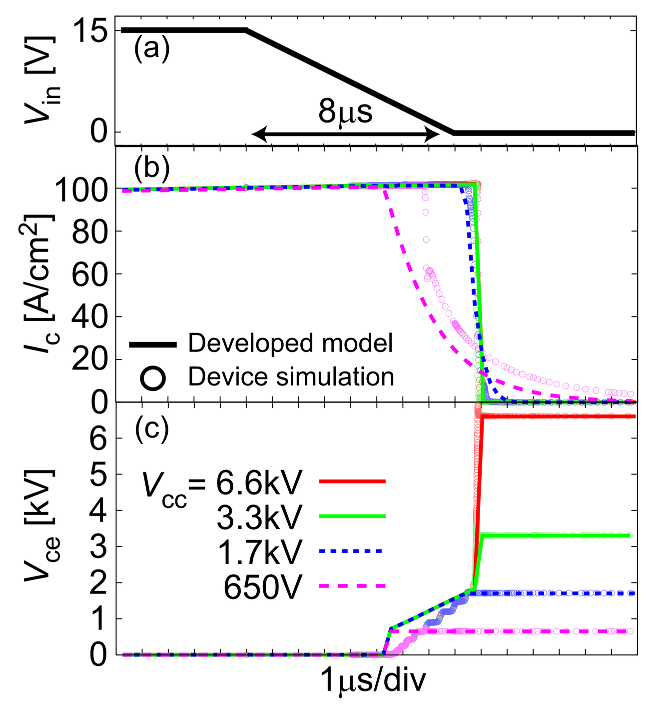
HiSIM-IGBT is verified to reproduce accurately the dynamic characteristics of Si IGBT circuits.

HiSIM-IGBT Extension and Verification for SiC

- To extend the HiSIM-IGBT model, the material parameters of SiC are included through the Poisson equation of the MOSFET part and through the excess carrier density in the base region.
- The punch though effect is included in the modeling of the base region.
- The model is implemented and verified in Spice3f5.



Carrier density is extremely low under the off state.



Absence of the tail current and the rapid increase of V_{ce} are reproduced correctly by the developed model.

Conclusions

- HiSIM-IGBT is extended to model the SiC IGBT device.
- Correct turn-off characteristics of the 4H-SiC IGBT for different supply voltages are verified, which is important for accurate calculation of energy loss and the ringing phenomena.

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