Study of High Precision IGBT Macro-Model Considering Temperature Dependency

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Outline

- Introduction
- Basic Principles of IGBTs
- Macro-Model Development
- Model Parameter Extractions and Simulations
- Conclusion

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Research Background

	Bipolar Transistor	**MOSFET**	**IGBT**
High voltage	☺	☹	☺
High speed switching	☹	☺	☺

- **Insulated Gate Bipolar Transistor (IGBT) is mainly applied for high voltage/current transistors in high power electric systems**

Research Purposes

Conventional simulation environment

○ Errors comparing with actual measurements are too large

Many Problems

- Can not characterize the drift current through the n-layer.
- The output resistance of DMOS part becomes constant.
- Free-wheel diode simulations are incorrect.

New simulation environment

- The model consists of only basic SPICE elements to improve accuracies.
- Drain current static characteristics are dependent on temperature.

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New simulation environment

- The model consists of only basic SPICE elements to improve accuracies.

- **without any source code modifications**
- **can be applied for any SPICE-compatible simulators**

Research Purposes

Conventional simulation environment

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New simulation environment

- Drain current static characteristics are dependent on temperature

▪make it possible for more practical simulations!

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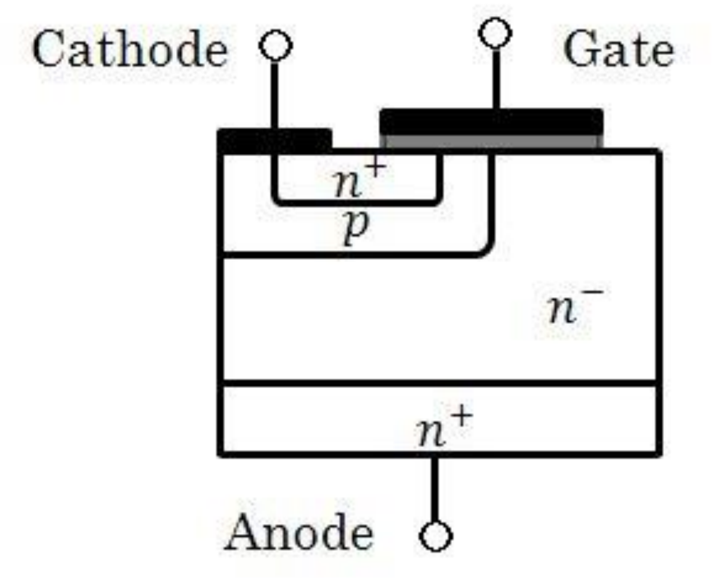
Typical Structure of an IGBT

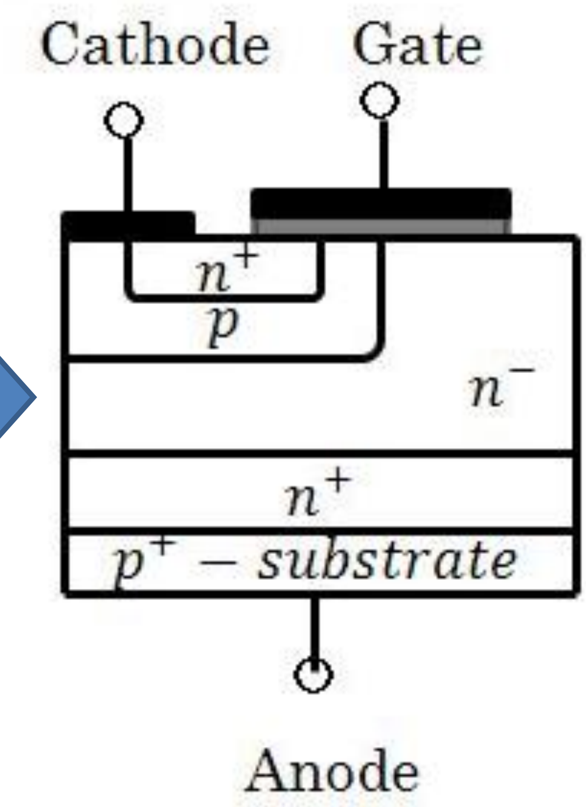


power MOSFET (DMOS transistor)

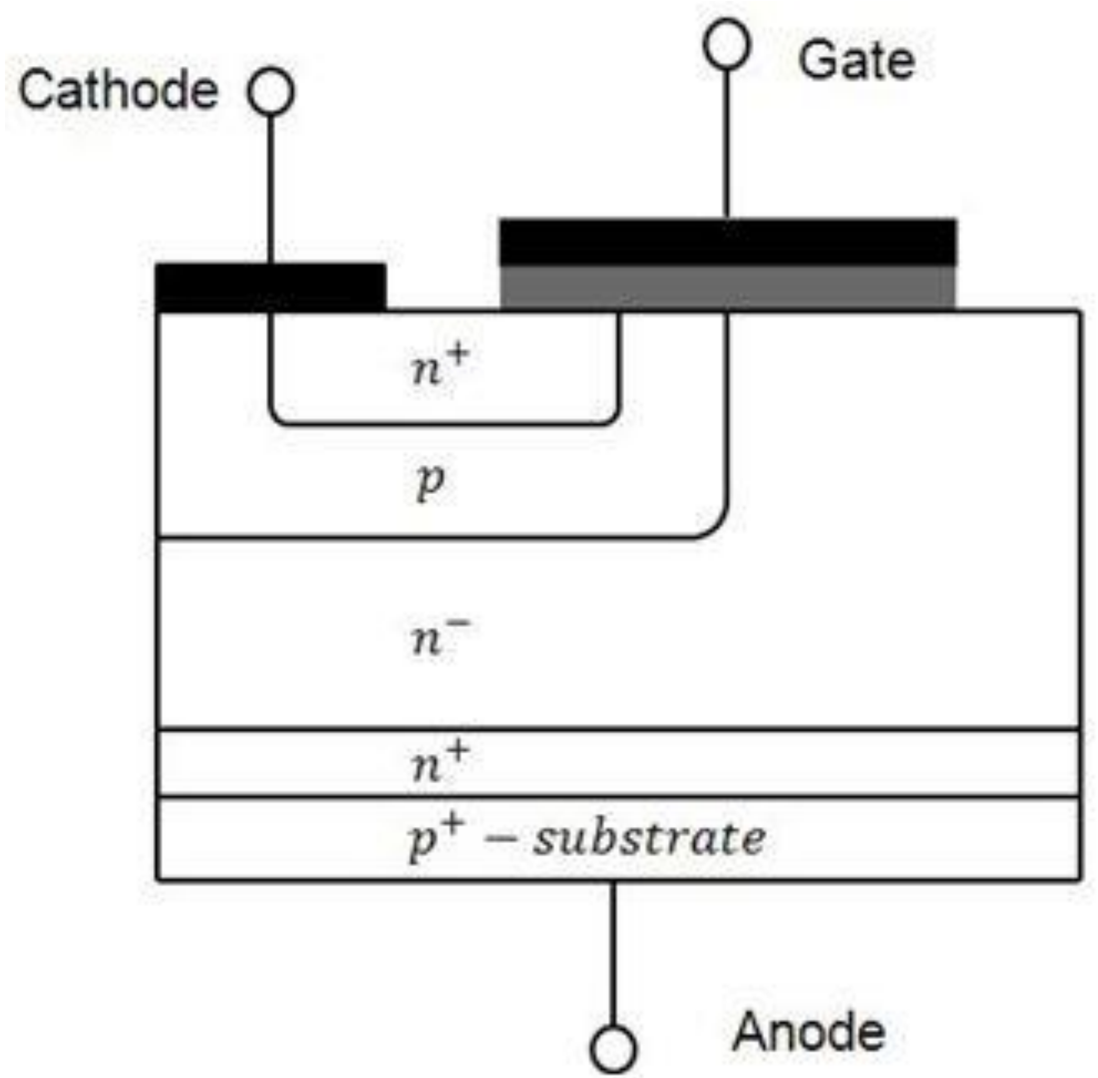
+

$p^+ - substrate$

appending the high diffusion rate p layer
on the DMOS structure.

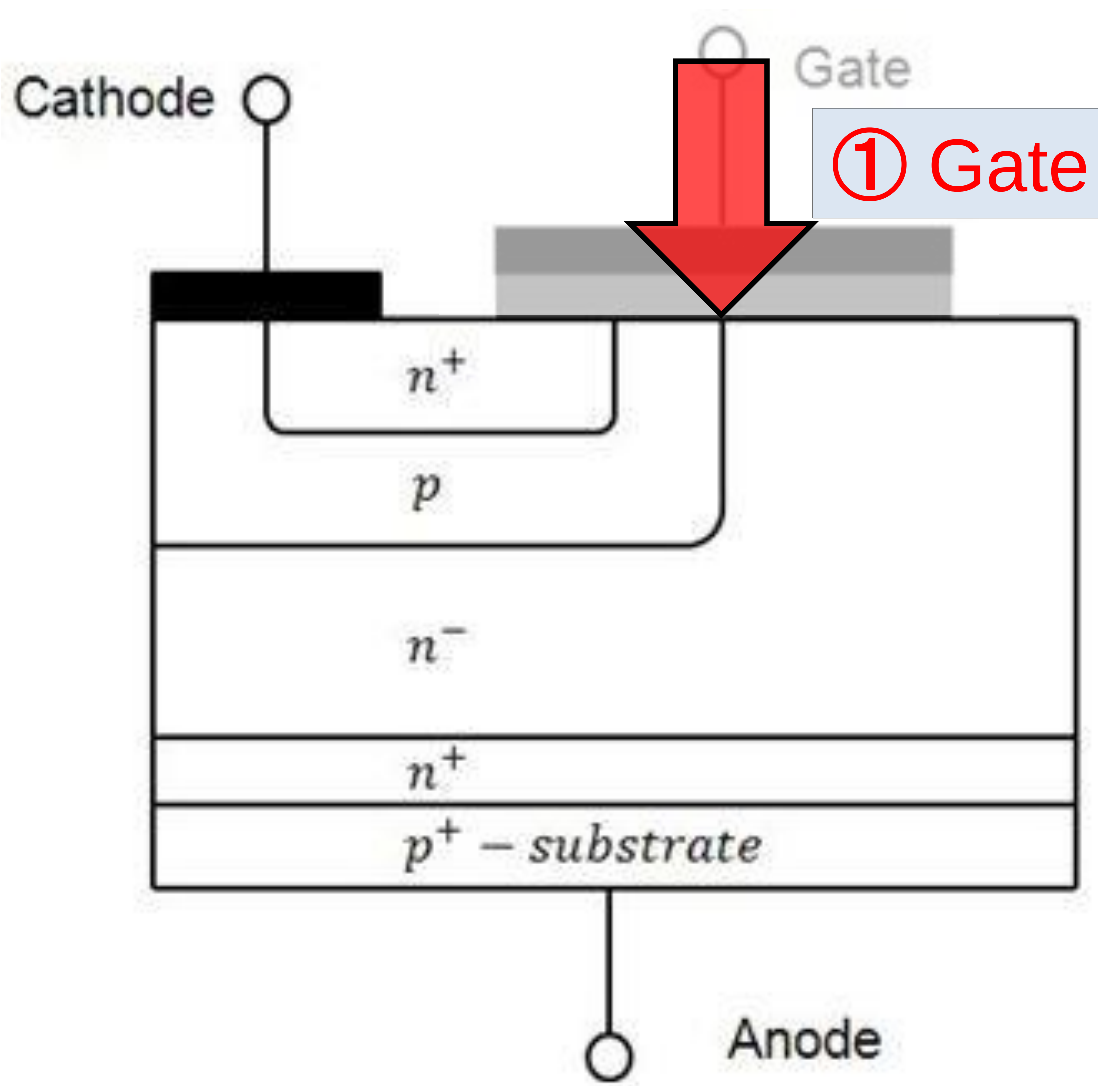


Conduction of an IGBT



Simplified device structure of an IGBT

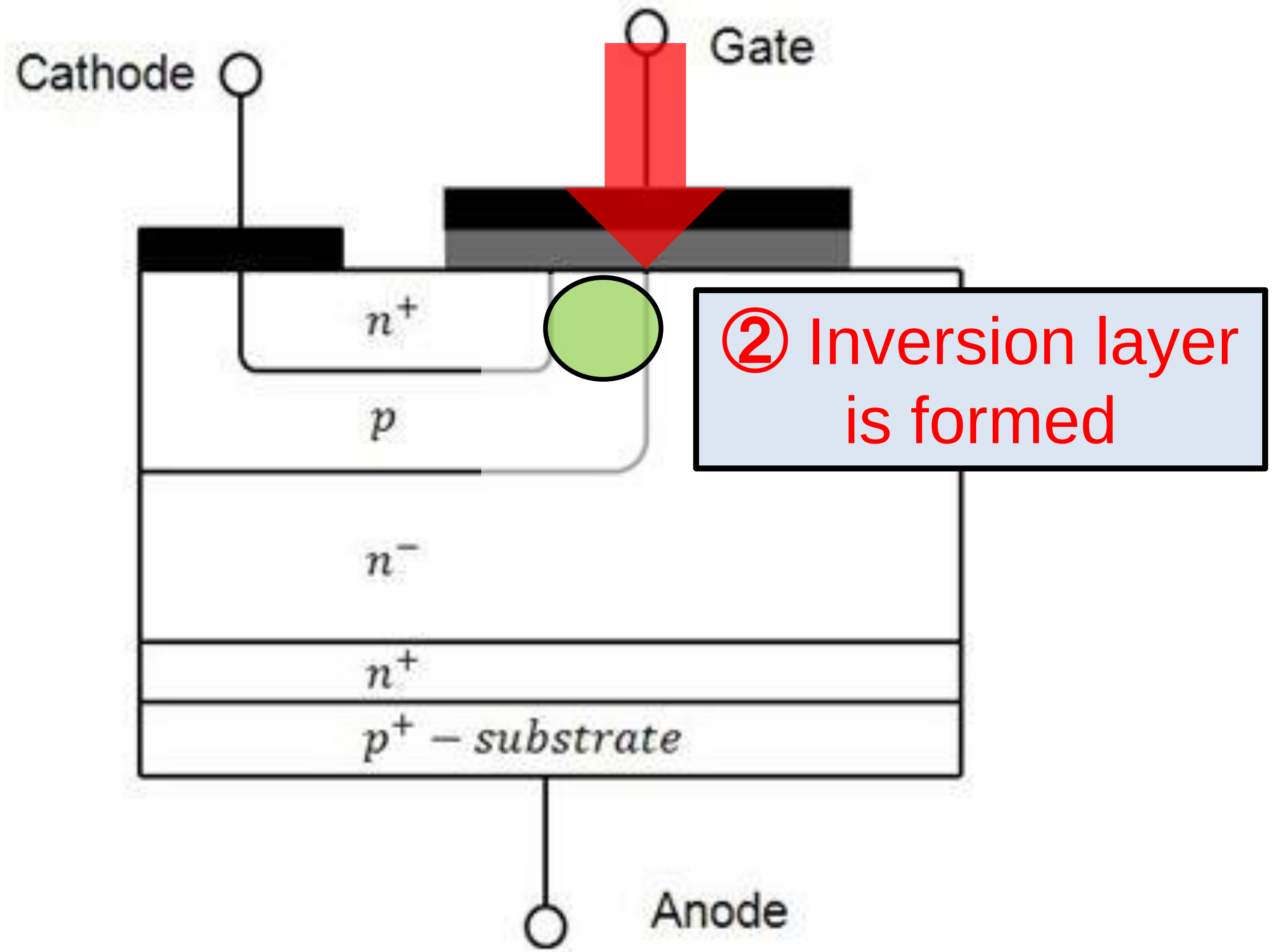
Conduction of an IGBT



① Gate voltage(V_G)

Simplified device structure of an IGBT

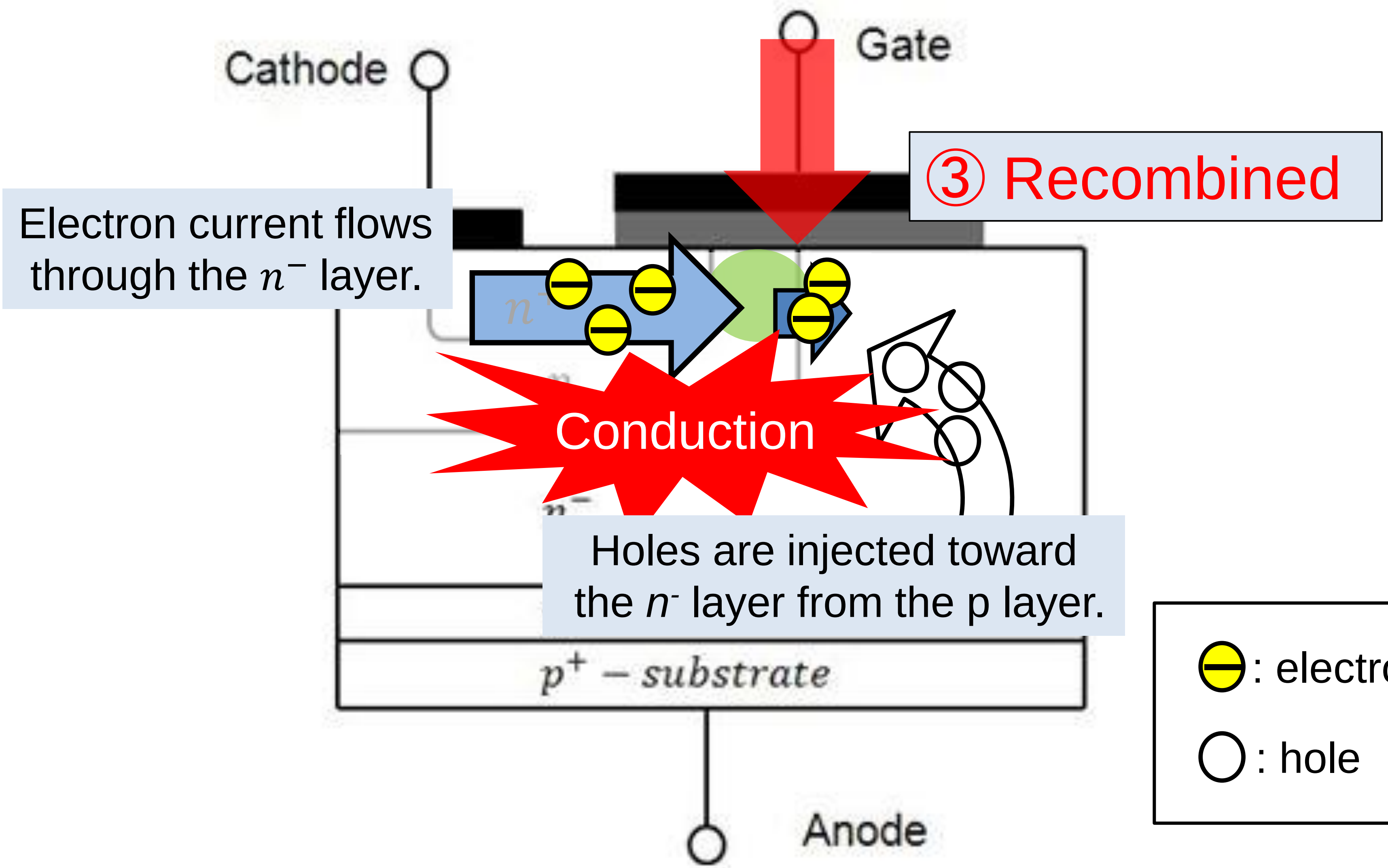
Conduction of an IGBT



② Inversion layer is formed

Simplified device structure of an IGBT

Conduction of an IGBT



Electron current flows through the n^- layer.

③ Recombined

Conduction

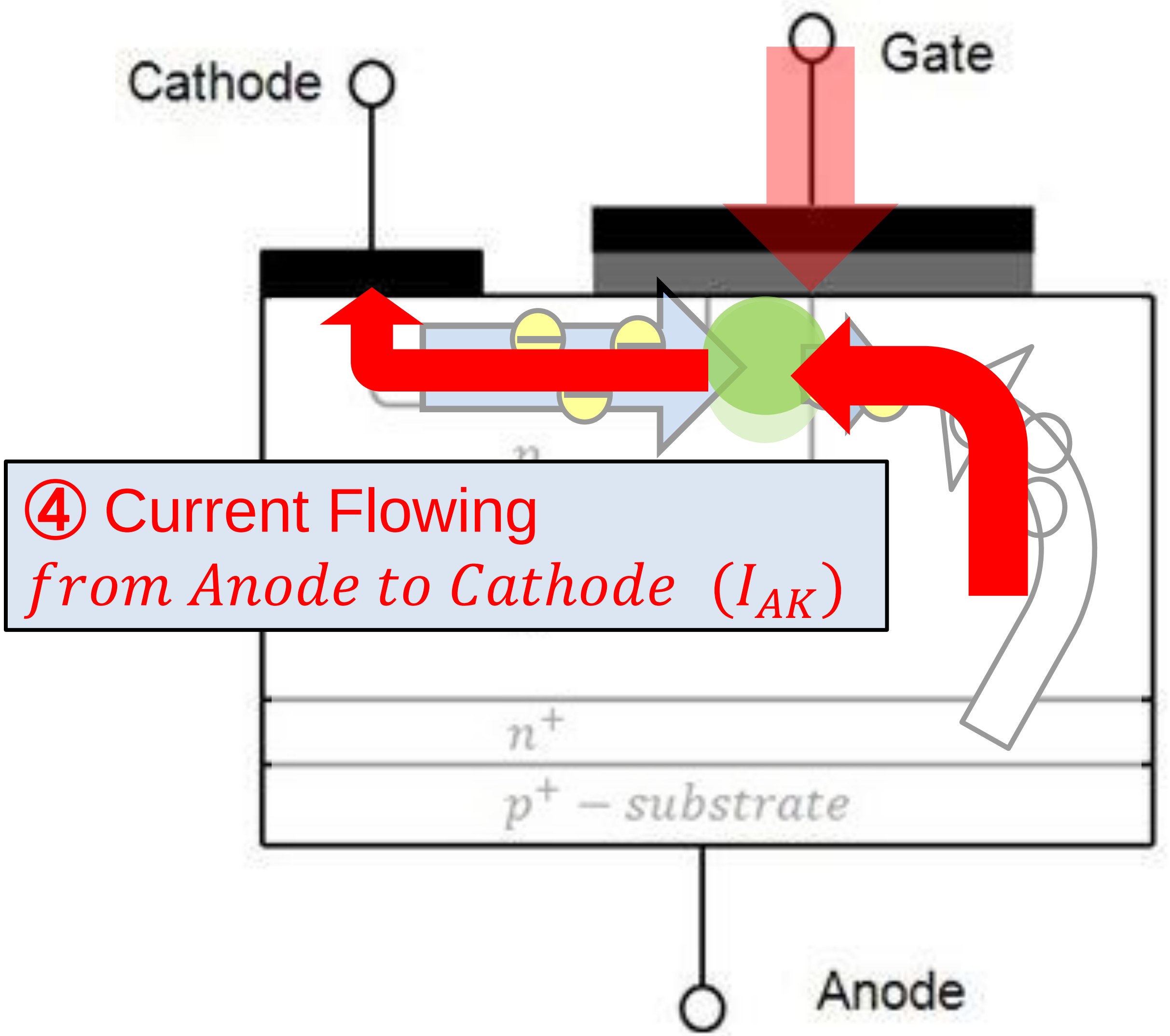
Holes are injected toward the n^- layer from the p layer.

⊖ : electron

○ : hole

Simplified device structure of an IGBT

Conduction of an IGBT

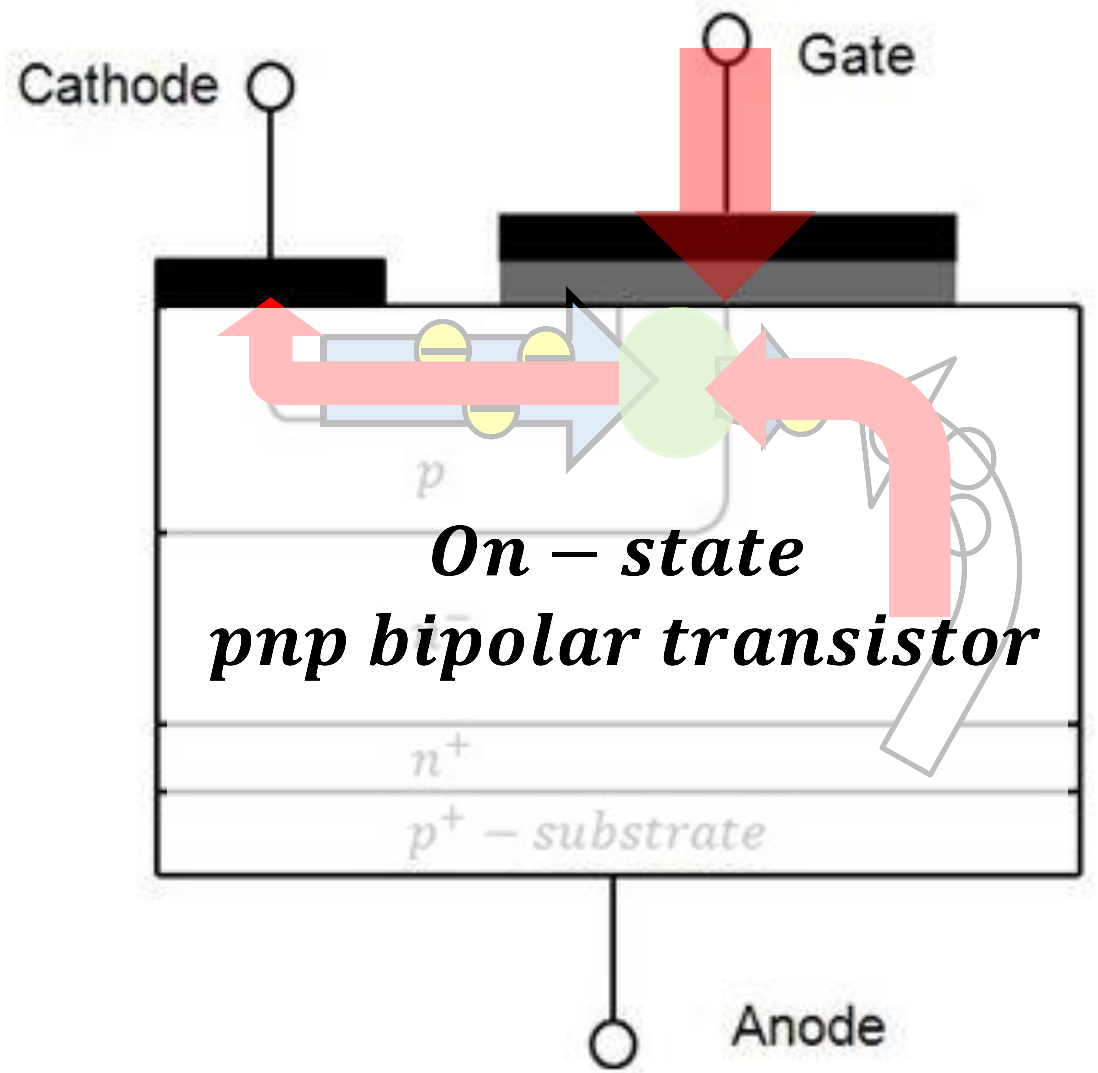


④ Current Flowing
from Anode to Cathode (I_{AK})

⊖ : electron
○ : hole

Simplified device structure of an IGBT

Conduction of an IGBT



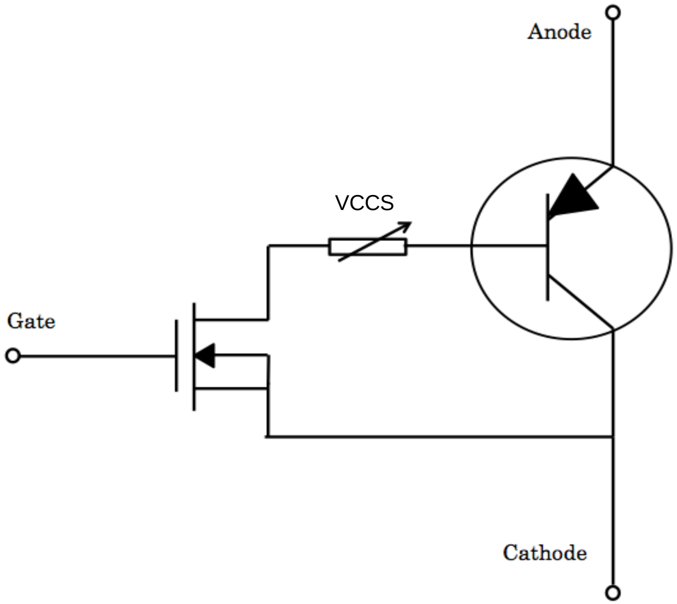
$$\boldsymbol{On - state}$$
$$\boldsymbol{pnp\ bipolar\ transistor}$$

Simplified device structure of an IGBT

⊖ : electron

○ : hole

Conventional IGBT Macro-model



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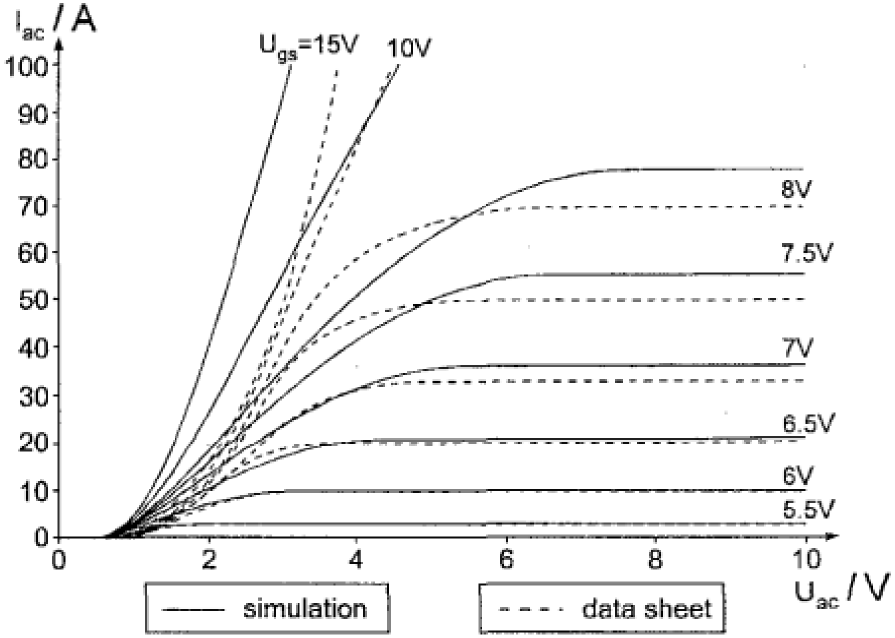

Anode DC current characteristic of the conventional IGBT model

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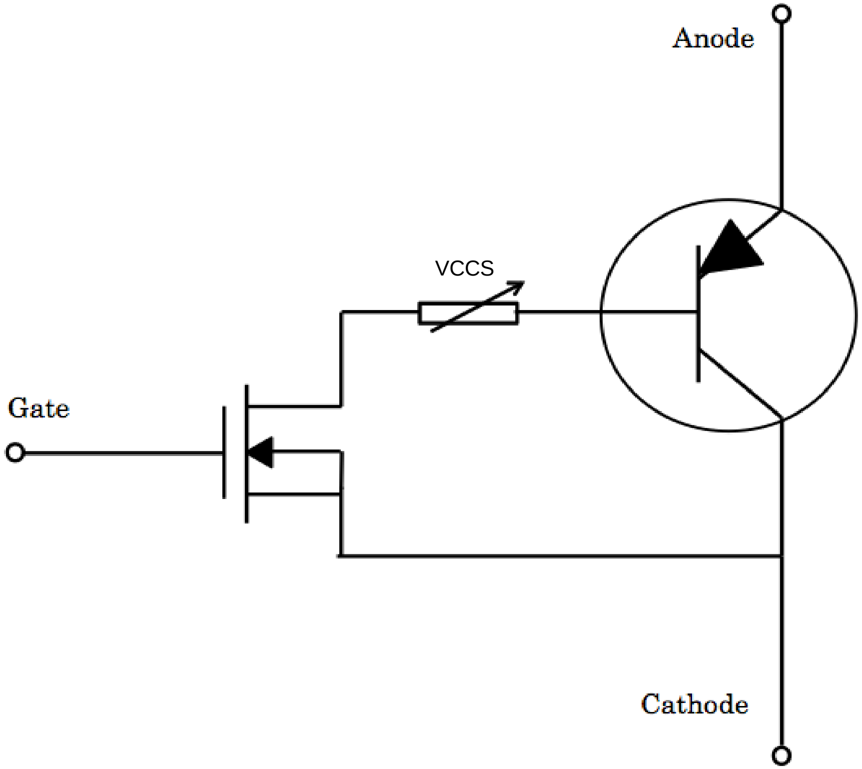

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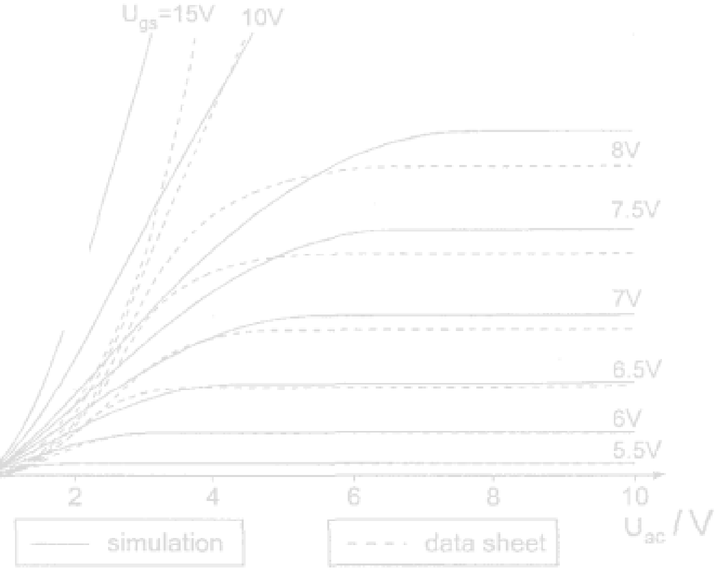
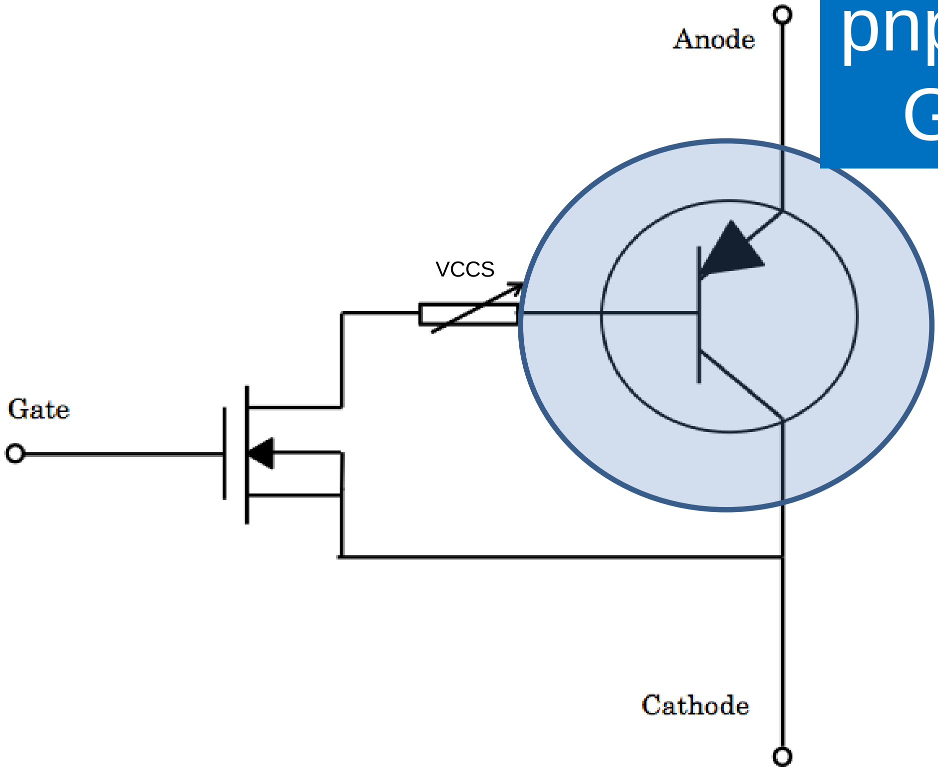


Anode DC current comparison of the conventional IGBT model

Conventional IGBT Macro-model

pnp bipolar transistor :
Gummel-Poon model



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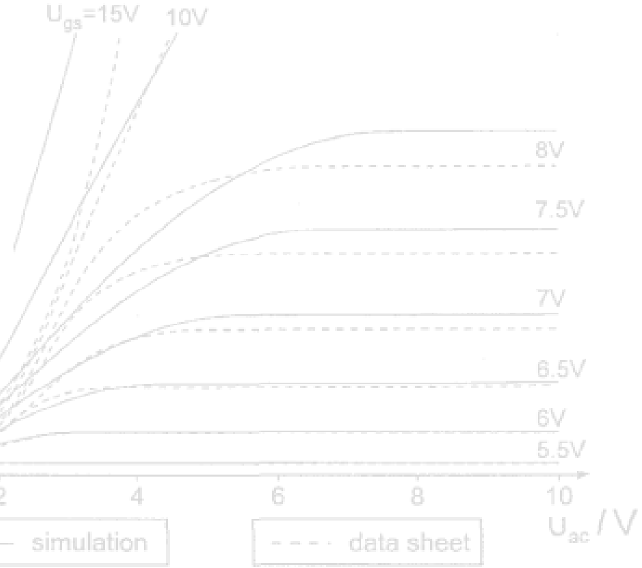

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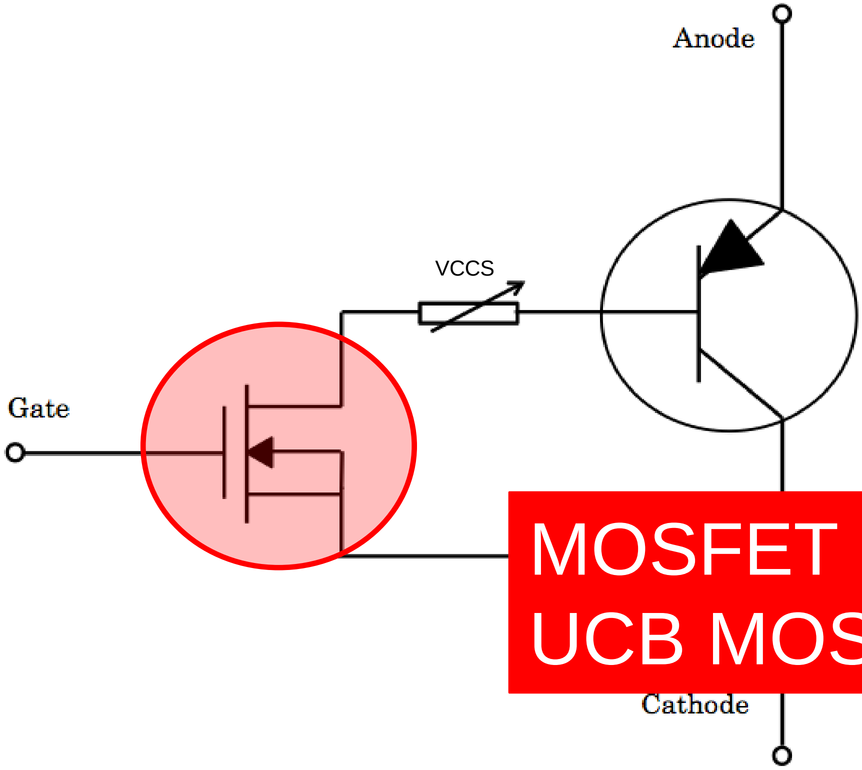
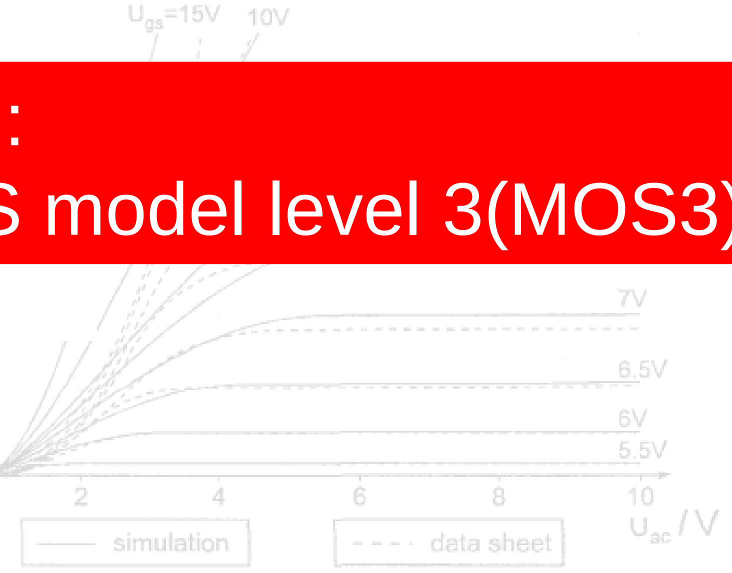


MOSFET :
UCB MOS model level 3(MOS3)

Conventional IGBT Macro-model



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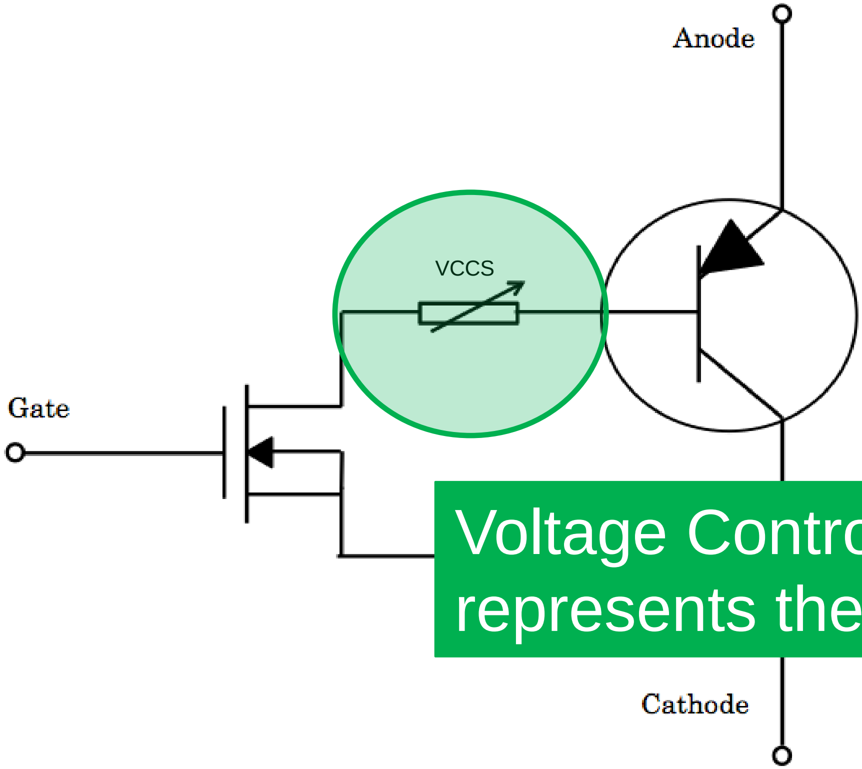
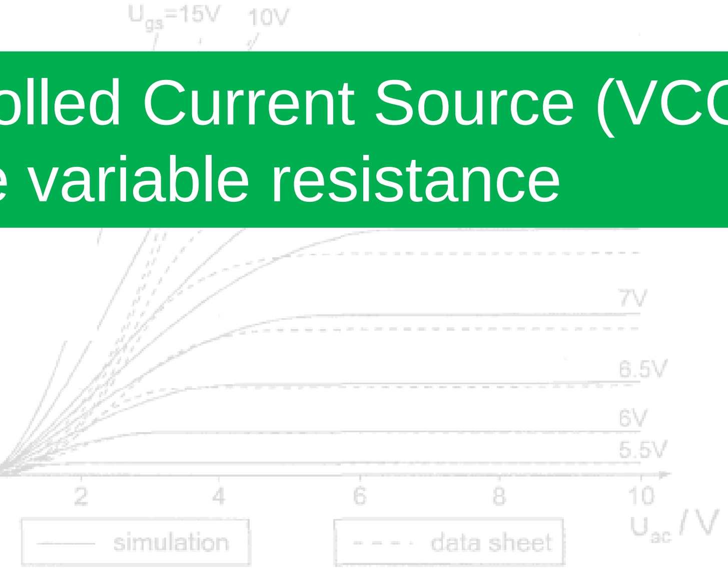


Voltage Controlled Current Source (VCCS) represents the variable resistance

Conventional IGBT Macro-model



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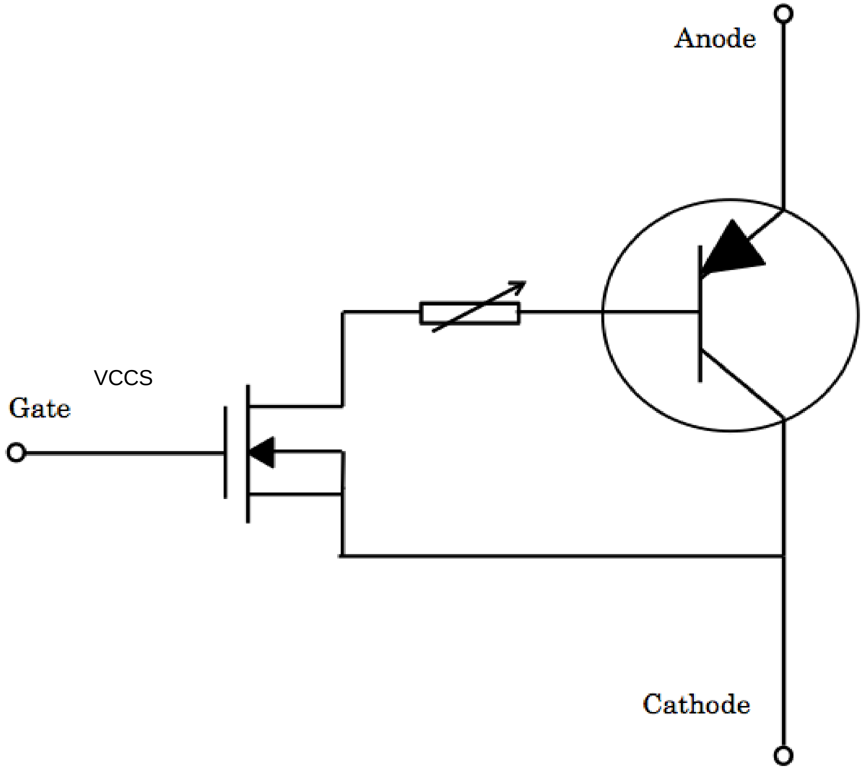
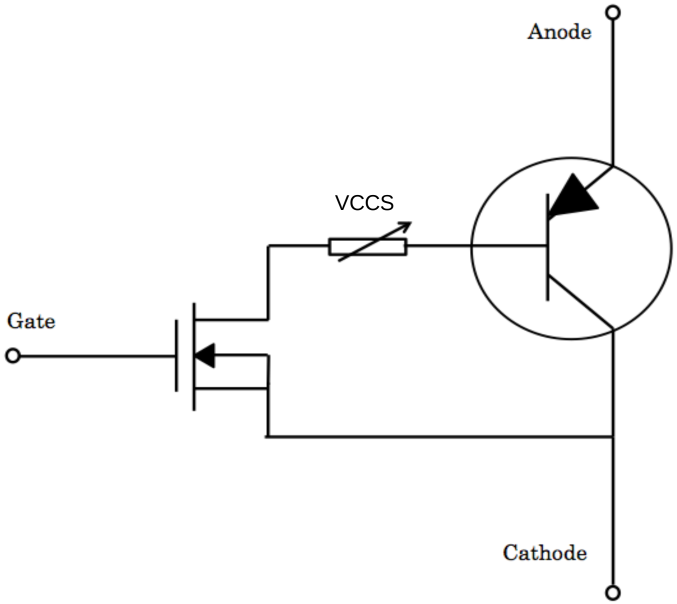


Conventional IGBT Macro-model

Disadvantage ：

- Can not characterize the drift current through the n-layer.
- The output resistance of DMOS part becomes constant.
- Free-wheel diode simulations are incorrect.

Conventional IGBT Macro-model



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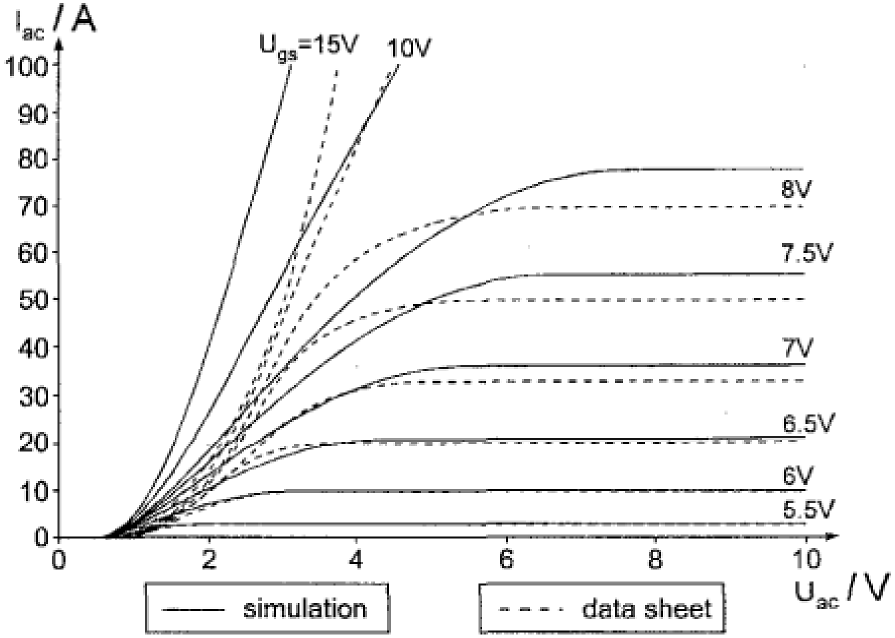

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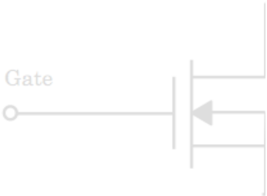

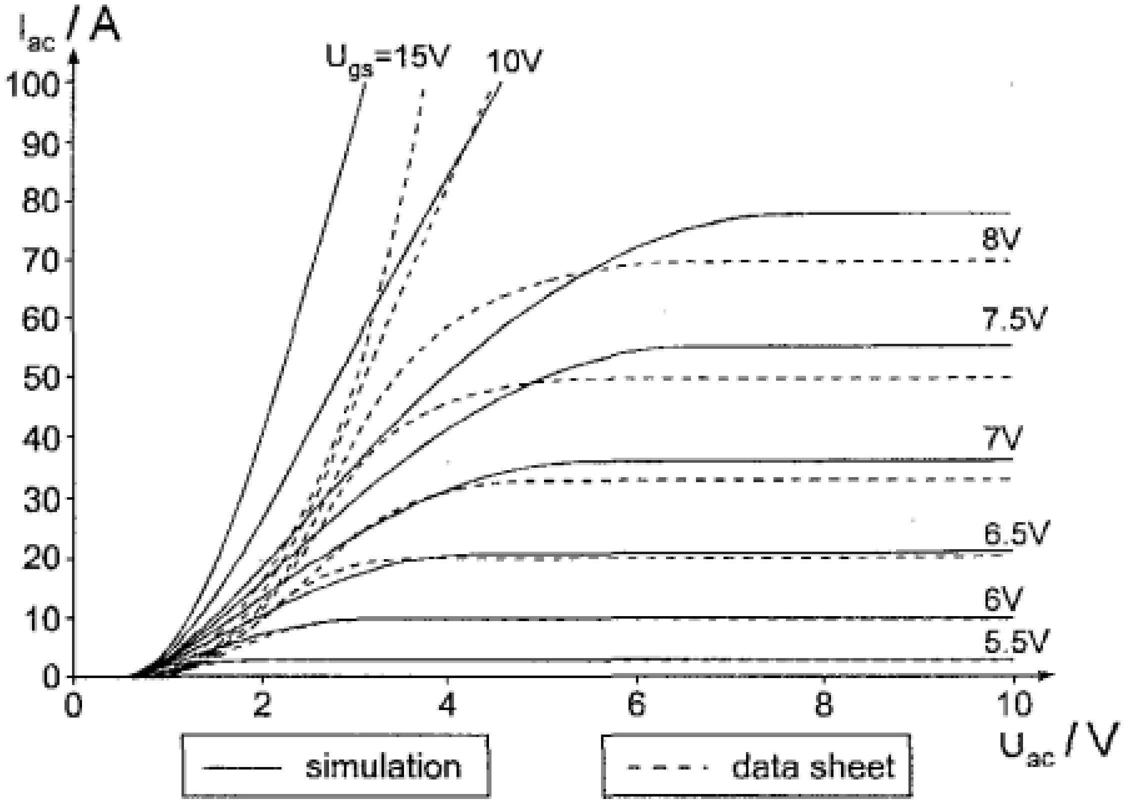

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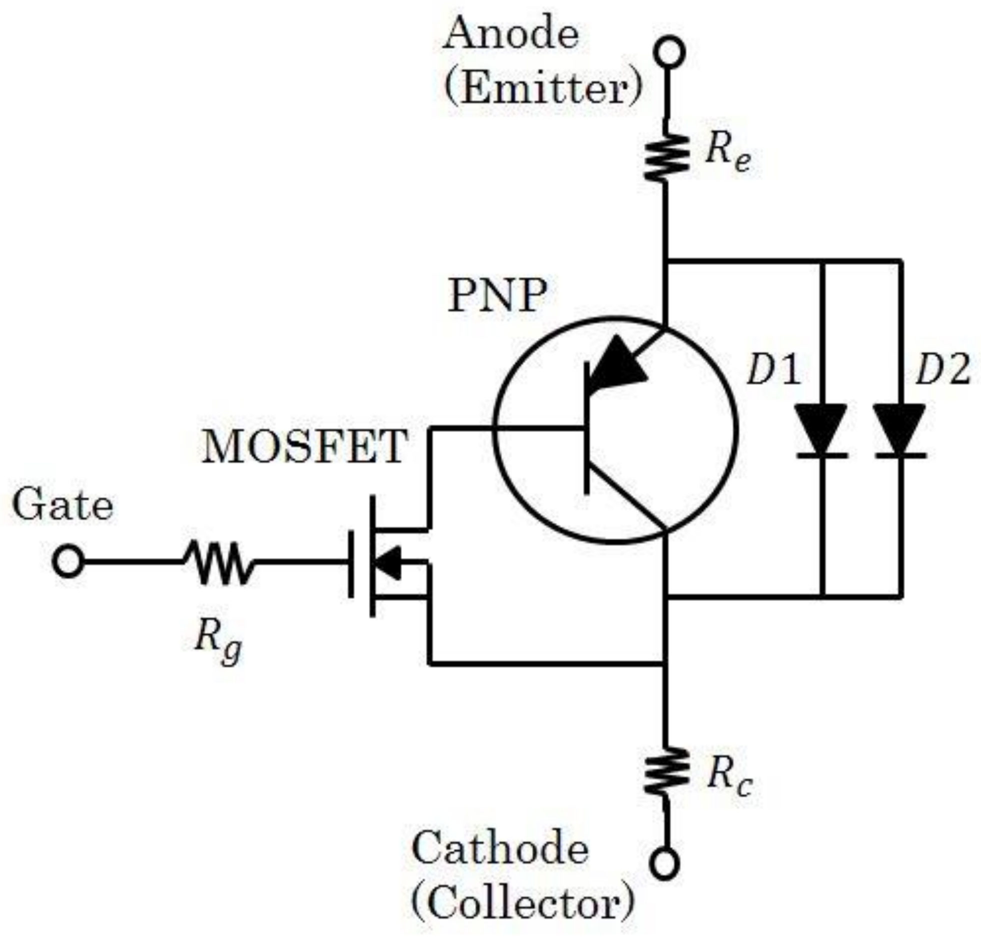
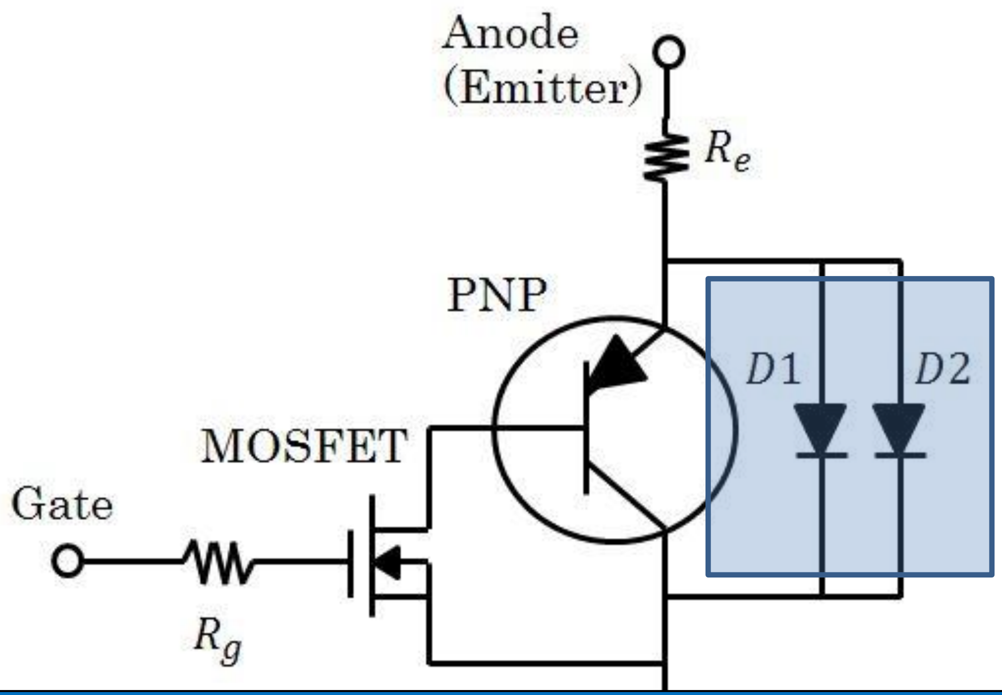
Proposed IGBT macro model



Proposed IGBT macro model : named as A(Aoki)-IGBT

Feature of A-IGBT model



Two pn diodes are connected in parallel,

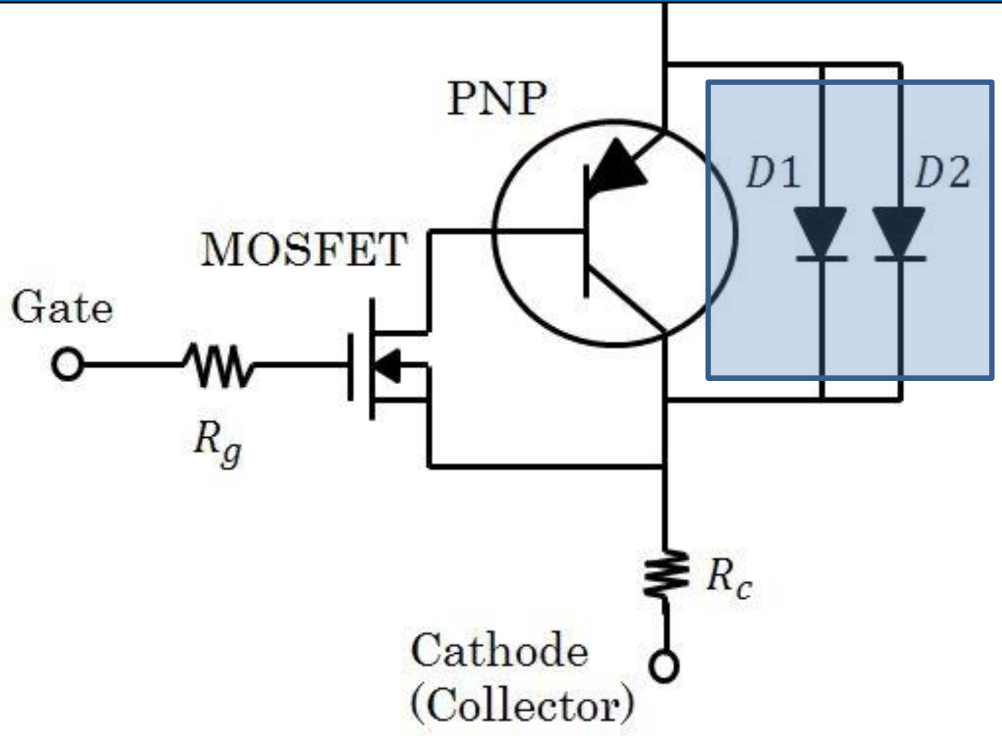
- which control the backward breakdown voltage of the n^- layer
- which simulate the forward current characteristics of the free-wheel diode

Proposed IGBT macro model : named as A-IGBT

Feature of A-IGBT model

Two pn diodes are connected in parallel,

- which increase the flexibility of the slope at current-voltage characteristic



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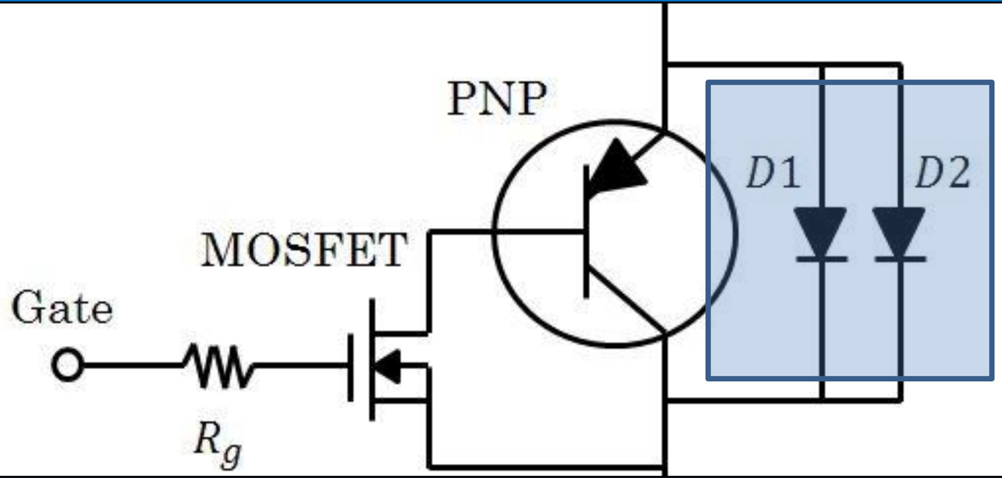

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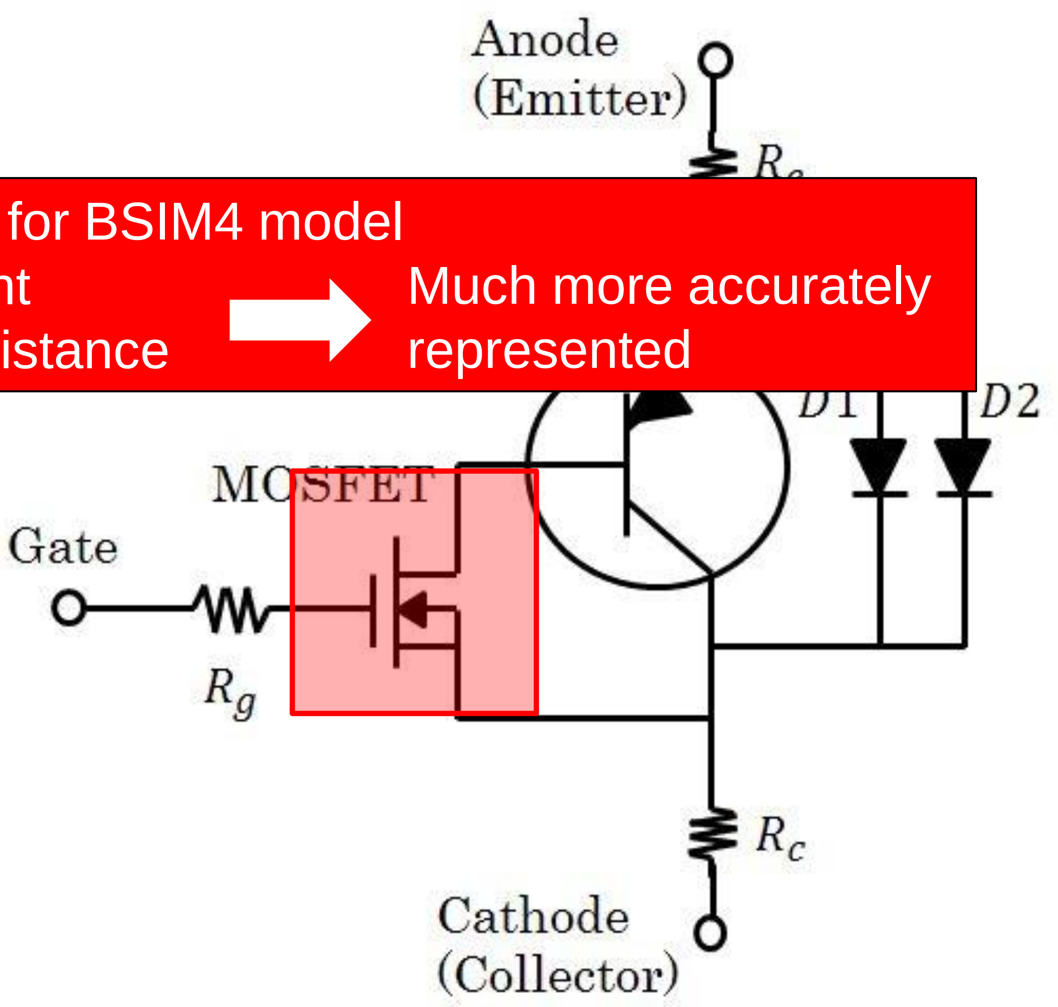

Swaps MOS3 for BSIM4 model

- Drift current
- Output resistance

→ Much more accurately represented

Proposed IGBT macro model : named as A-IGBT

Current Drift Mobility Model

UCB MOS model level3 (MOS3)

$$\mu_{eff} = \frac{\mu_0}{1 + \frac{\mu_s \cdot V_{DS}}{V_{MAX} \times L_{eff}}}$$

$$\mu_s = \frac{U0}{1 + THETA(V_{GS} - VTH)}$$

BSIM4

$$\mu_{eff} = \frac{U0 \cdot f(L_{eff})}{1 + [UA(\frac{V_{gsteff} + 2V_{th}}{TOXE}) + UB(\frac{V_{gsteff} + 2V_{th}}{TOXE})^2]} \cdots$$

$$\cdots \frac{}{(1 + UC \cdot V_{vseff}) + UD(\frac{V_{th} \cdot TOXE}{V_{gsteff} + 2V_{th}})^2}$$

Output Resistance Model

MOS3

$$R_d = const$$

BSIM4

The output resistance (R_{ds}) is coupled to the drain current

The model is considering in 3 saturation regions

- CLM (Channel length modulation) effect
- DIBL (Drain Induced Barrier Lowering) effect
- SCBE (Substrate Current Body Effect)

$$\begin{aligned} I_{ds} \quad = \quad & \frac{I_{dso}\cdot NF}{1+\frac{R_{ds}I_{ds0}}{V_{dseff}}}\left[1+\frac{1}{C_{clm}\log e\left(\frac{V_A}{V_{Asat}}\right)}\right]\cdot \\ & \left(1+\frac{V_{ds}-V_{dseff}}{V_{ADIBL}}\right)\left(1+\frac{V_{ds}-V_{dseff}}{V_{ADITS}}\right)\left(1+\frac{V_{ds}-V_{dseff}}{V_{ASCBE}}\right) \end{aligned}$$

Temperature Dependencies Model

- Drain current equations dependent on ambient temperature

Mobility

$$UX(T) = UX(TNOM) + UX1 \cdot (T/TNOM - 1)$$

Saturation Velocity

$$VSAT(T) = VSAT(TNOM) - AT \cdot (T/TNOM - 1)$$

Including temperature terms!

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Extraction・Optimization

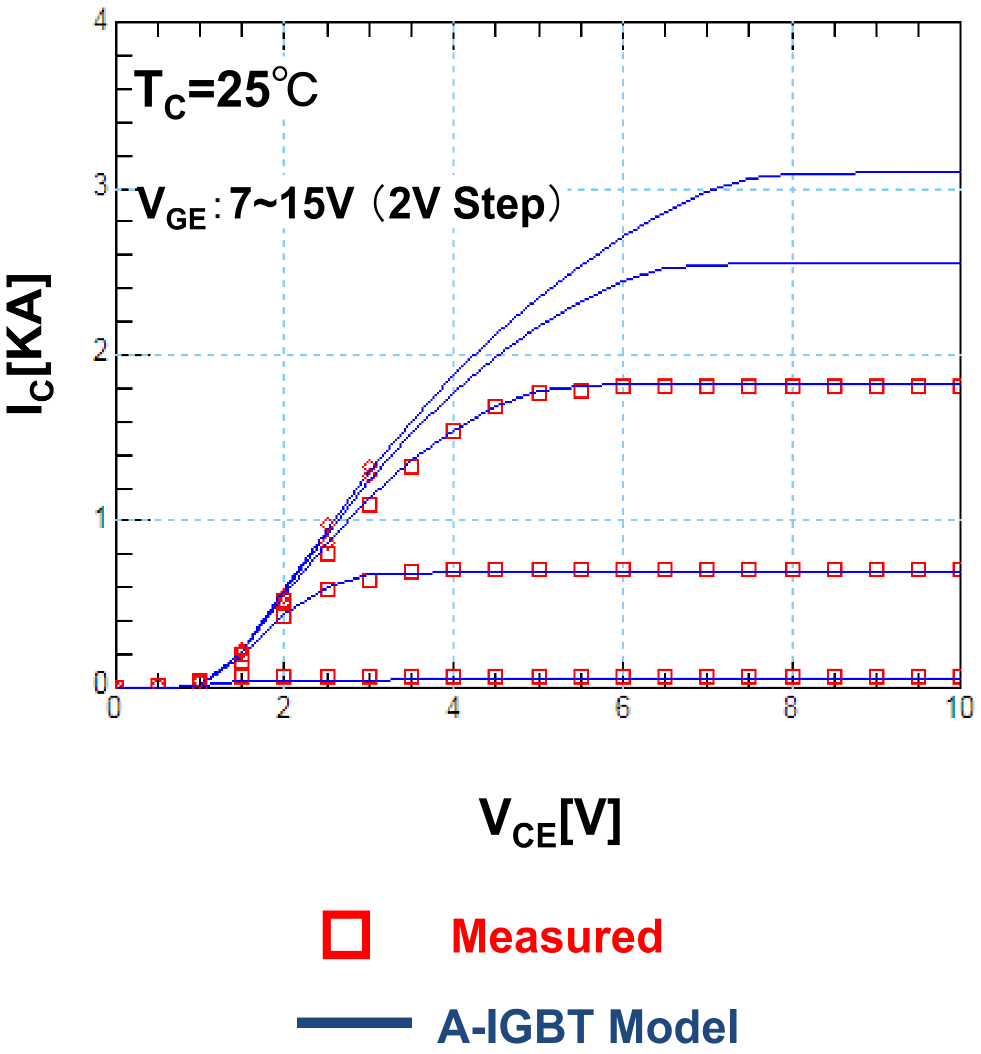
USING DATA SHEET

・IGBT MBN1200E33E made by HITACHI

1. Implemented in SPICE
   - BSIM4 model
   - Gummel-Poon model
   - PN diode model

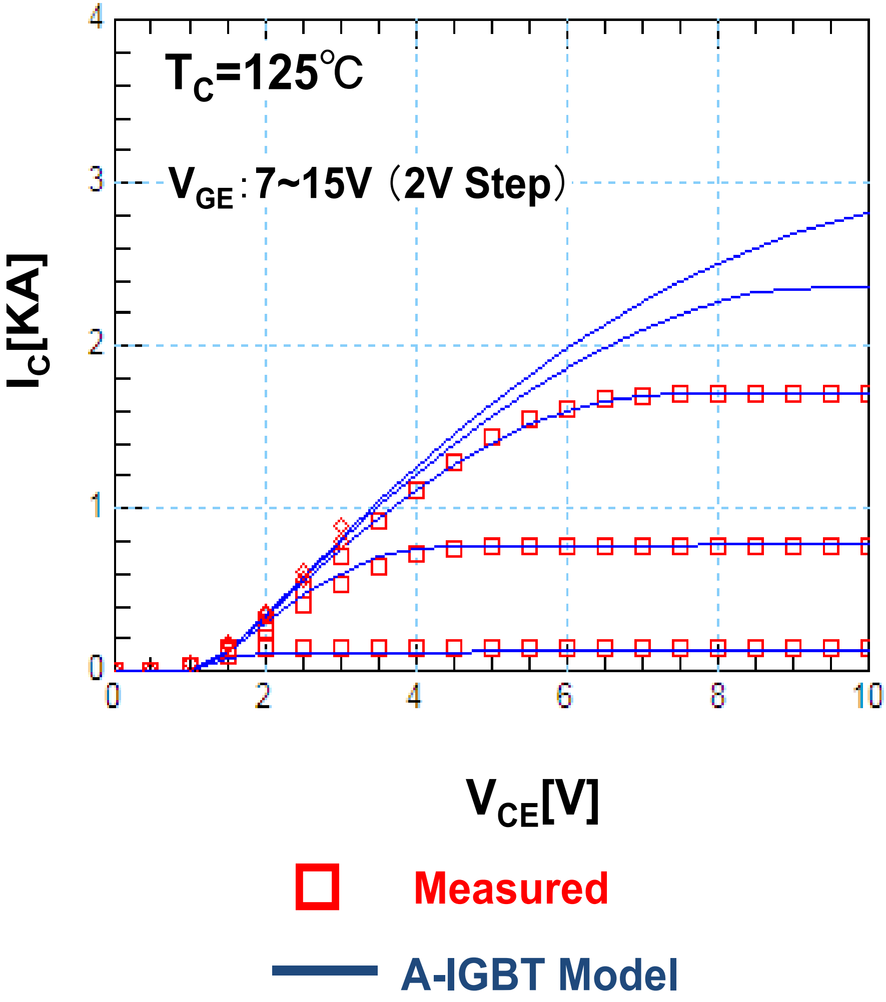
2.Extractions and Optimizations
   - Model parameters

Simulation Result ($T_C = 25$℃)



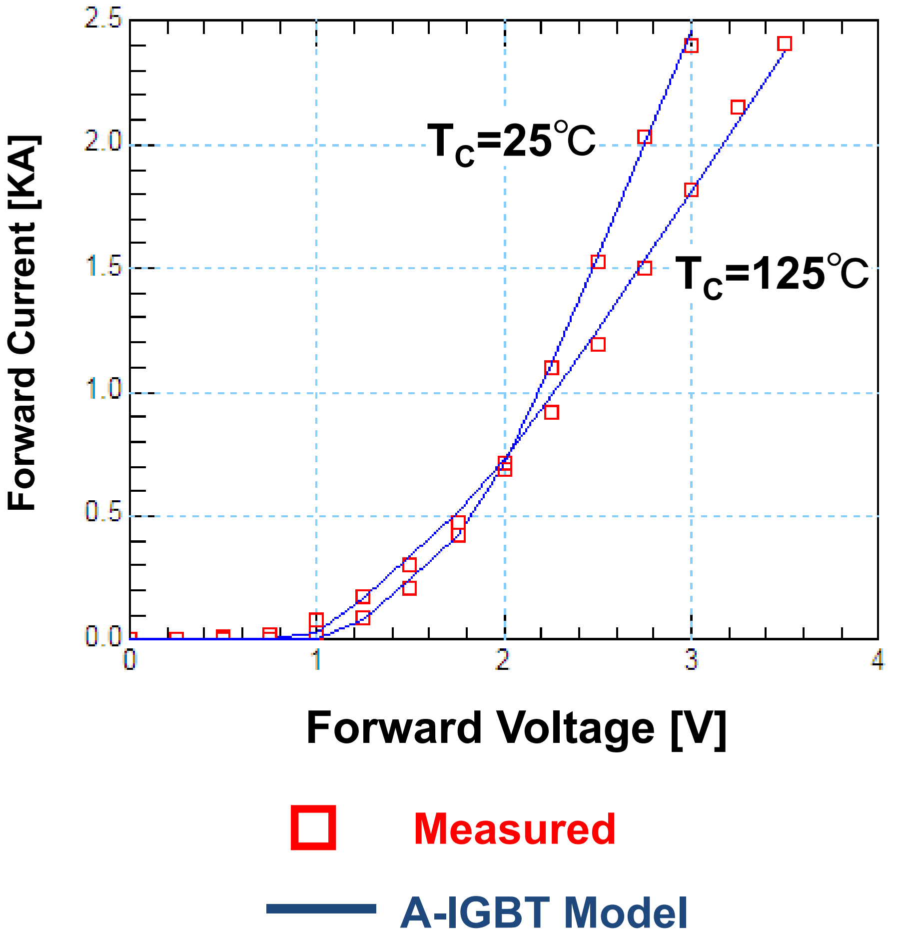
Gate resistance dependency of V_{CE} is accurately simulated

Simulation Result ($T_C = 125$℃)



Comparison between measured from Datasheet and simulated collector-emitter currents of an IGBT

Simulation Result (free-wheel diode)



Measurement from Datasheet and simulation results of forward current of free-wheel diode

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Conclusions

- New IGBT macro-model for SPICE simulators is developed
- Accurate model parameters are extracted by using the DC I-V measurements
- The A-IGBT model can simulate static current dependent on temperature, accurately
- Simulation results with the proposed A-IGBT model agreed with measured data from data sheets, accurately.

Future work

- Continue to develop the capacitance model of IGBTs in order to complete our A-IGBT model by verifying the switching characteristics