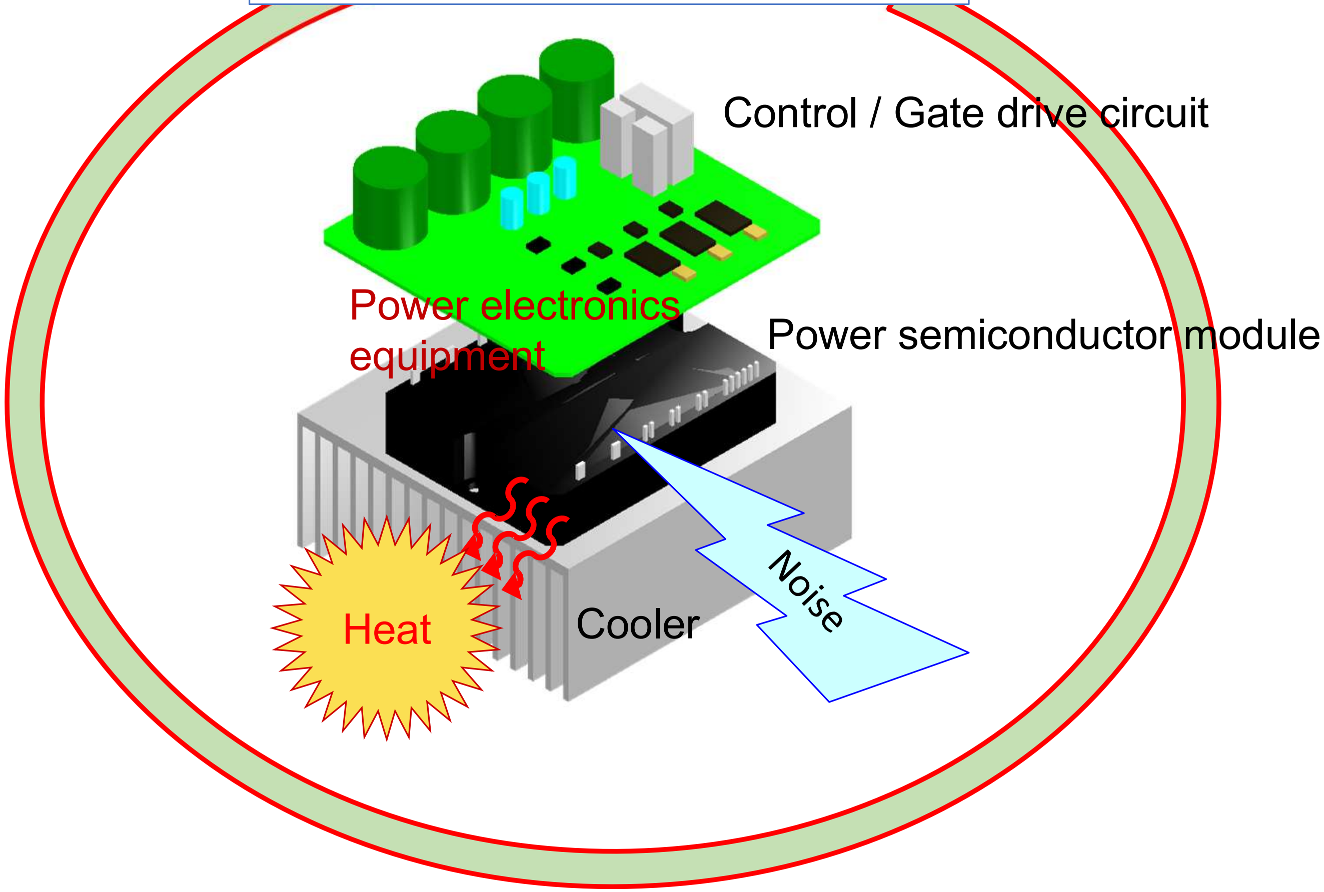
1. Development of power semiconductor device models

①中嶋，堀口，浦壁，萩原,
「SiC-MOSFET，GaN-HEMTに適用可能なユニバーサルデバイスモデルの開発」,
令和３年電気学会全国大会，WEB17-B2・パワーエレクトロニクスデバイス評価・4-001（2021）
②J. Nakashima, T. Horiguchi, Y. Mukunoki, M. Hagiwara, T. Urakabe and S. Harada,
“Automated Flexible Modeling for Various Full-SiC Power Modules”,
IEEE Transactions on Power Electronics (Early Access)，pp. 1-15（2023）
③井口，原田，浦壁，中嶋，堀口，椋木,
「温度特性を考慮したGaNデバイスモデルの研究」,
電気学会 電子デバイス/半導体電力変換 合同研究会，EDD-23-037/SPC-23-220，2023

Purpose: Construction of an accurate and easy-to-use power semiconductor model for virtual production and verification of power electronics equipment utilizing simulation technology

Simulation（Analysis）



1. Building an I_D-V_{DS} model for power semiconductor devices

Modeling method（@MATLAB）

Step.1
Import the actual measurement data (I_D vs. V_{DS}). Extract the values of the variables Func1, Func2, and Func3 in the basic model formula for each V_{GS} data.

↓

Step.2
Model the extracted Func1, Func2, Func3 data with a Gaussian function as a function of V_{GS}.

↓

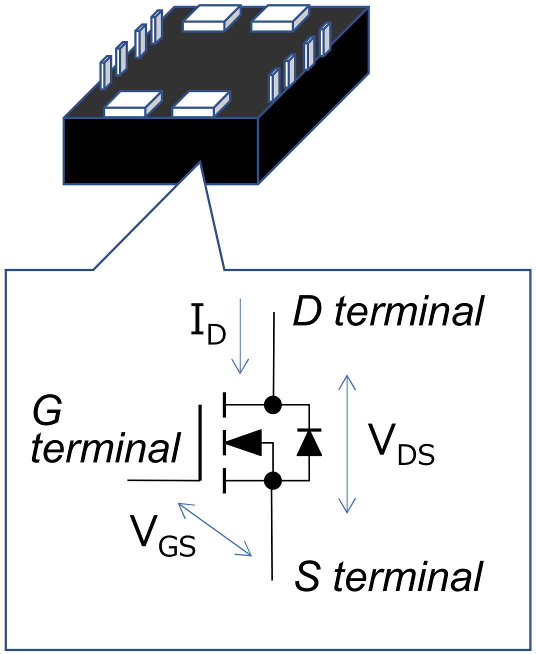
Step.3
Replace Func1 ~ 3 model with basic model formula.

↓

Power semiconductor model is completed

Target : 1.2kV-Full SiC module

Power semiconductor module



Power semiconductor device

Step.1

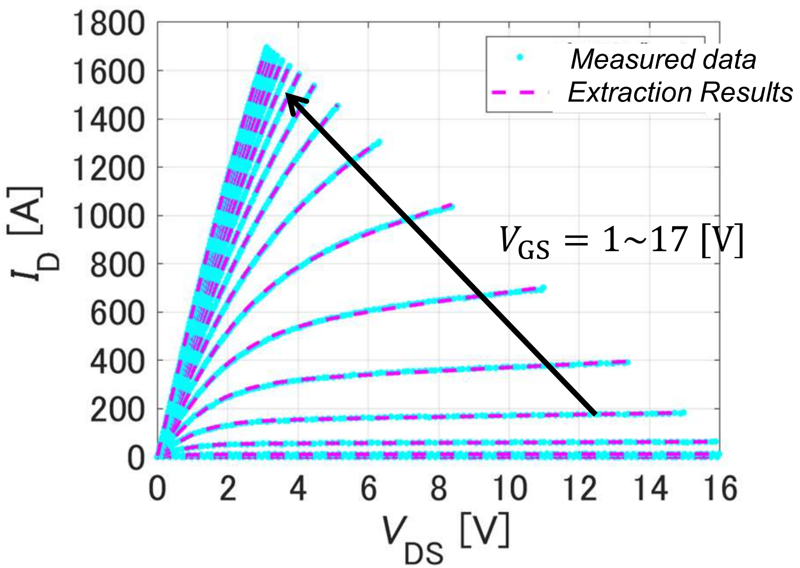
Import the actual measurement data (I_D vs. V_{DS}). Extract the values of the variables Func1, Func2, and Func3 in the basic model formula for each V_{GS} data.

∗ Fitting measured data with Func1,2,3.

Basic model formula :

$$I_{D(V_{DS})} = f_{(\mathbf{Func1}, \mathbf{Func2}, \mathbf{Func3}, V_{DS})}$$

$$= \mathbf{Func1} \times tanh(\mathbf{Func2} \times V_{DS} \cdots) + \cdots$$



Target : 1.2kV-Full SiC module

Step.2

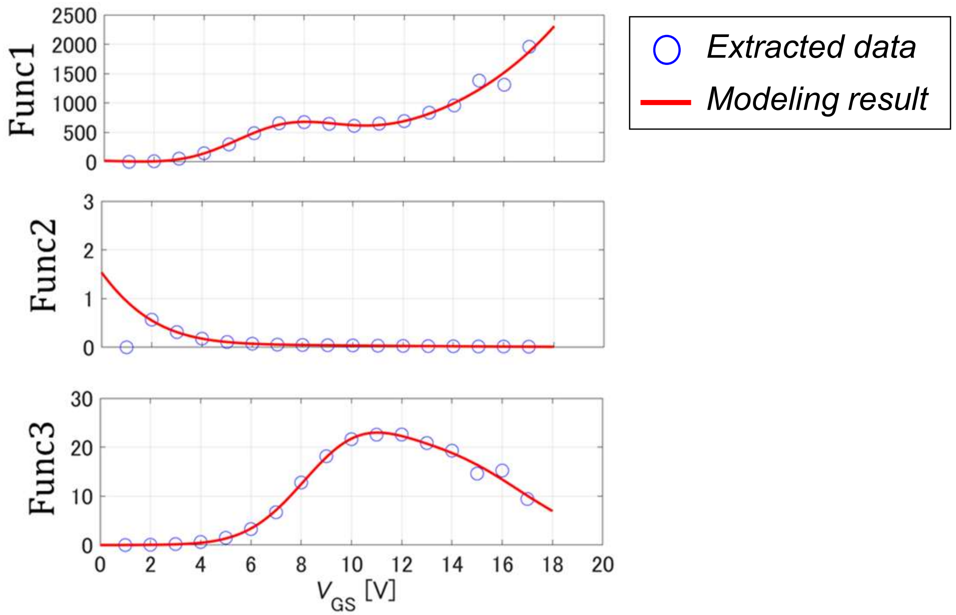
Model the extracted Func1, Func2, Func3 data with a Gaussian function as a function of V_{GS} .

$$\mathrm{Func1}_{(V_{GS})} = \sum_{i=1}^{n} \mathbf{A1}_i \times e^{-\left(\frac{V_{GS} - \mathbf{B1}_i}{\mathbf{C1}_i}\right)^2}$$

$$\mathrm{Func2}_{(V_{GS})} = \sum_{i=1}^{n} \mathbf{A2}_i \times e^{-\left(\frac{V_{GS} - \mathbf{B2}_i}{\mathbf{C2}_i}\right)^2}$$

$$\mathrm{Func3}_{(V_{GS})} = \sum_{i=1}^{n} \mathbf{A3}_i \times e^{-\left(\frac{V_{GS} - \mathbf{B3}_i}{\mathbf{C3}_i}\right)^2}$$

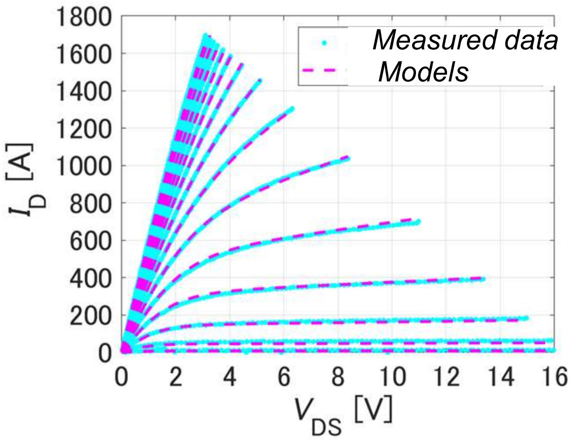
$\mathbf{A1}_i \sim \mathbf{C3}_i$: Constant parameter



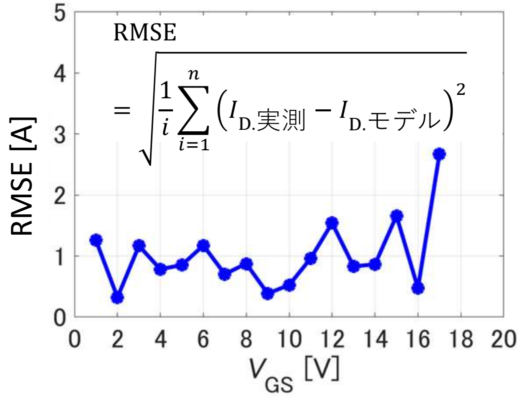
Step.3
Replace Func1 ~ 3 model with basic model formula.

＊*Power semiconductor model is completed*

$$I_{\mathrm{D}(V_{\mathrm{DS}},V_{\mathrm{GS}})} = f_{\left(\mathrm{Func1}_{(V_{\mathrm{GS}})},\mathrm{Func2}_{(V_{\mathrm{GS}})},\mathrm{Func3}_{(V_{\mathrm{GS}})},V_{\mathrm{DS}}\right)}$$



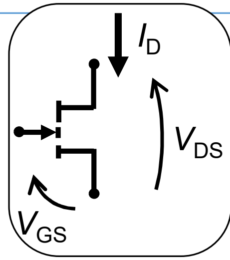
Compare the measured data with the model



Mean square error between measured data and model

Target : 1.2kV-Full SiC module

2. I_D-V_{DS} modeling of GaN power semiconductor devices with temperature characteristics



Modeling method（@MATLAB）

Step.1
25°C model is created using the modeling method described above.

$$I_D = F1_{(V_{GS})} \times \left(2 - e^{\frac{-V_{DS}}{F2_{(V_{GS})}}}\right) \times \tanh\left(-\frac{V_{DS}}{F3_{(V_{GS})}}\right)$$

↓

Step.2
Adding temperature terms to the model equation obtained in step 1.

$$I_D = F_{temp1} \times F1_{(V_{GS})} \times \left(2 - e^{\frac{-V_{DS}}{F2_{(V_{GS})}}}\right) \times \tanh\left(-\frac{V_{DS}}{F3_{(V_{GS})}} \times F_{temp2}\right)$$

↓

Step.3
Taking the measured data (I_D vs. V_{DS} for each temperature) and extract the values of variables F_{temp1} and F_{temp2} in the basic model equations for each V_{GS} and temperature T data (GA).

↓

Step.4
Modeling the extracted F_{temp1} and F_{temp2} data as a function of V_{GS} and T.

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Step.5
Substituting F_{temp1} and F_{temp2} models into the basic model equation.

$$I_D = F_{temp1(V_{GS},T)} \times F1_{(V_{GS})} \times \left(2 - e^{\frac{-V_{DS}}{F2_{(V_{GS})}}}\right) \times \tanh\left(-\frac{V_{DS}}{F3_{(V_{GS})}} \times F_{temp2(V_{GS},T)}\right)$$

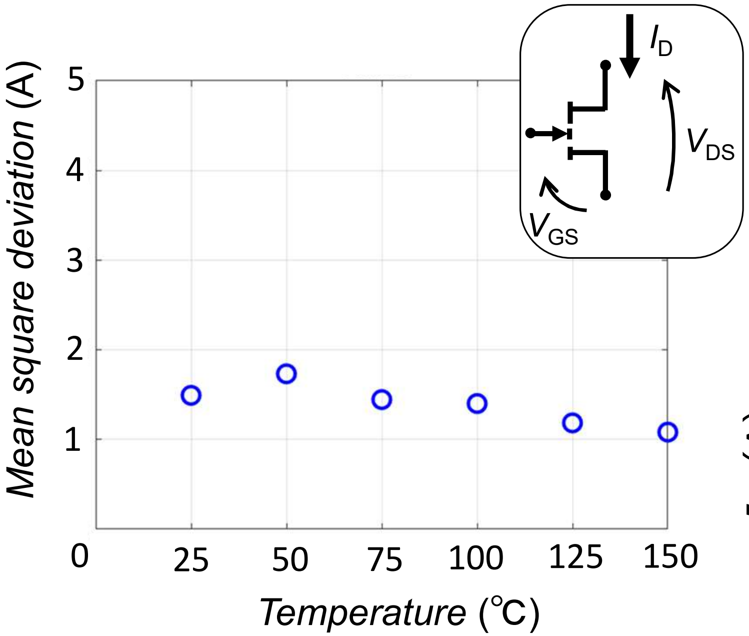
↓

Power semiconductor model is completed

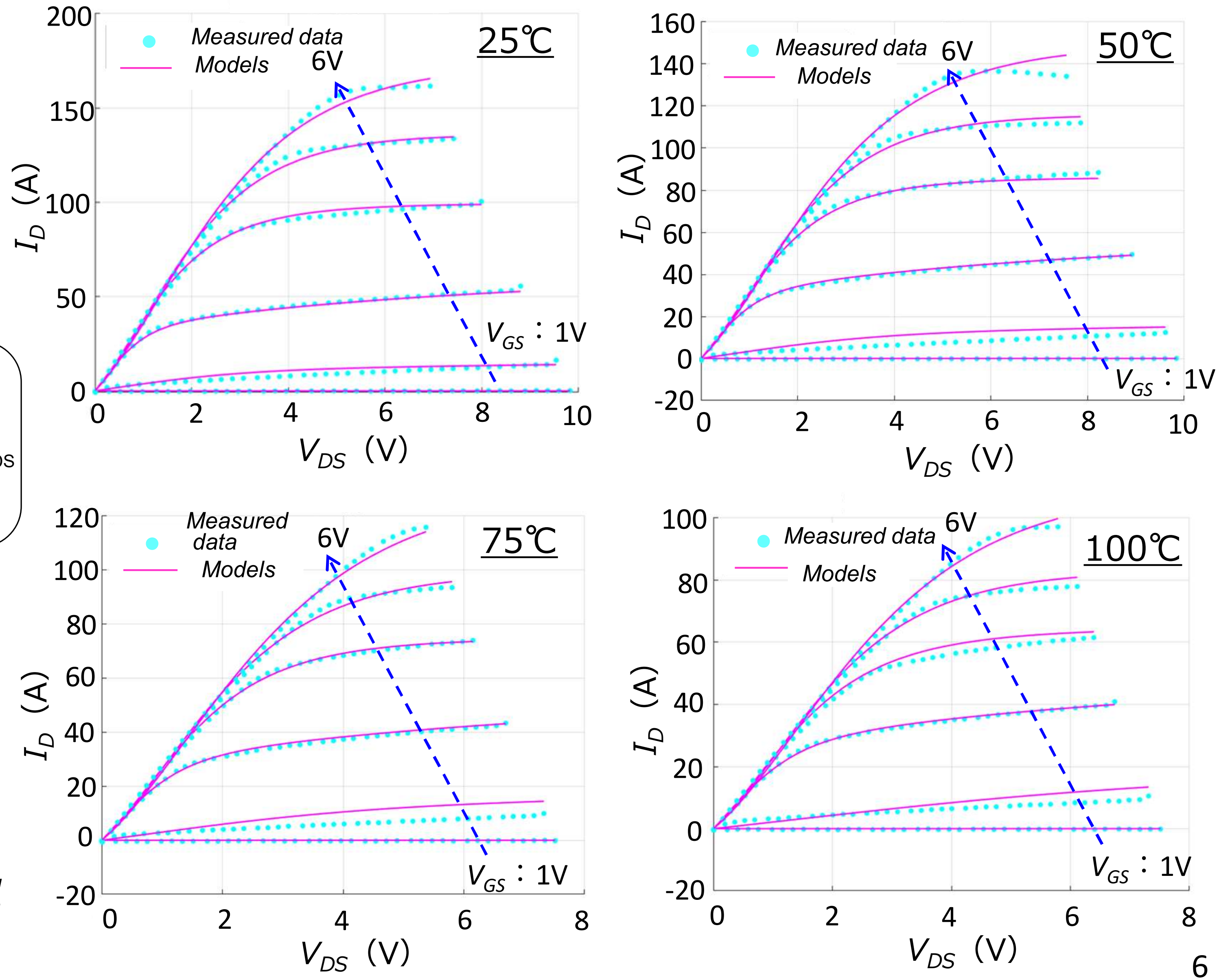
Target：GS66516B（650V/60A）GaN-HEMT

GaN Power Semiconductor Device Comparison of measured data and model

Mean square deviation between actual and model is 1.47A (2.5% of 60A rating) in the range of 25 to 150°C.

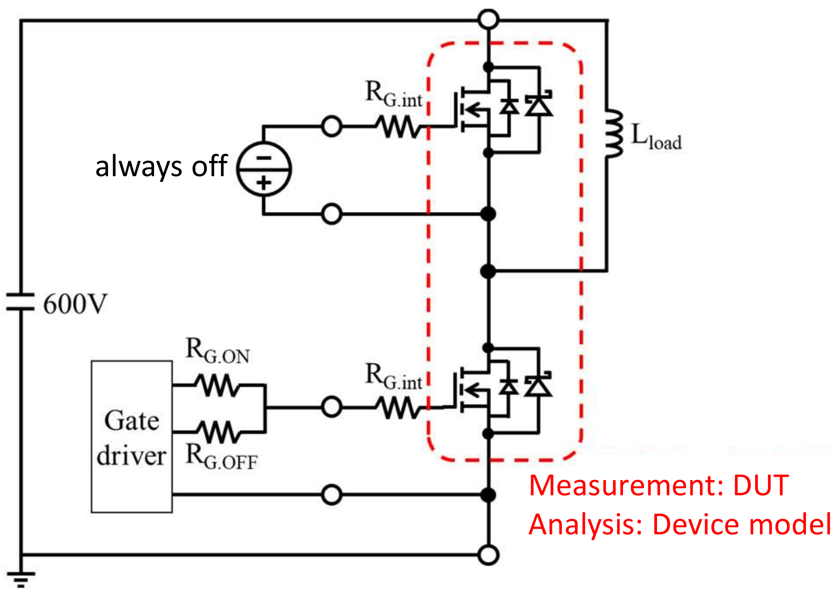


Mean square deviation between actual and model at each temperature



2. Matching the switching characteristics of the model with those of the semiconductor device

①Measuring switching waveforms using a test circuit



Configuration of the test circuit

②Add tuning parameters to the model

Add tuning parameters to I_D-V_{DS} models, C_{GS} models, C_{DG} models

③Set objective function for tuning

Calculating the difference between the measured waveform and the analysis waveform for the following items under each current

RMSE I_G: Error between measurement and analysis I_G
RMSE V_G: Error between measurement and analysis V_G
RMSE dI_D/dt: Error between measurement and analysis dI_D/dt
RMSE dV_{DS}/dt: Error between measurement and analysis dV_{DS}/dt

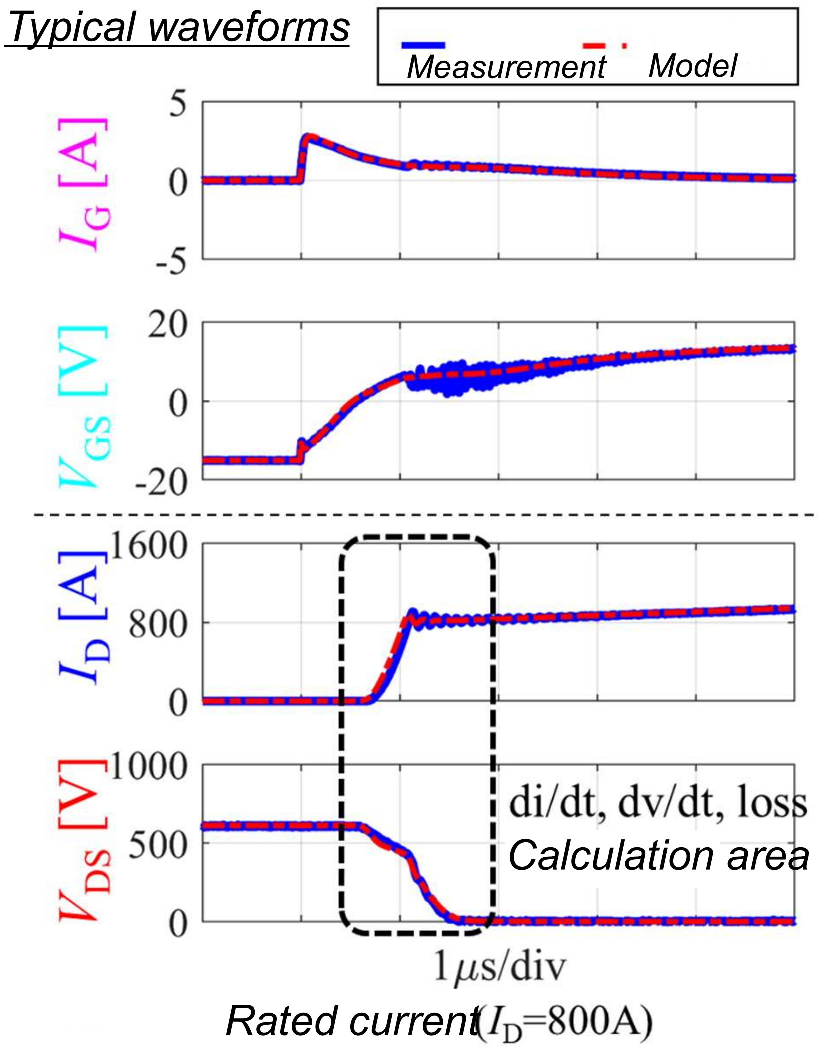
$$I_{G.ON.RMSE} = \sqrt{\frac{1}{16}\sum_{i=1}^{16}\left\{\left(\Delta I_{G.ON(@I_D=i\times 100[A])}\right)^2\right\}}$$

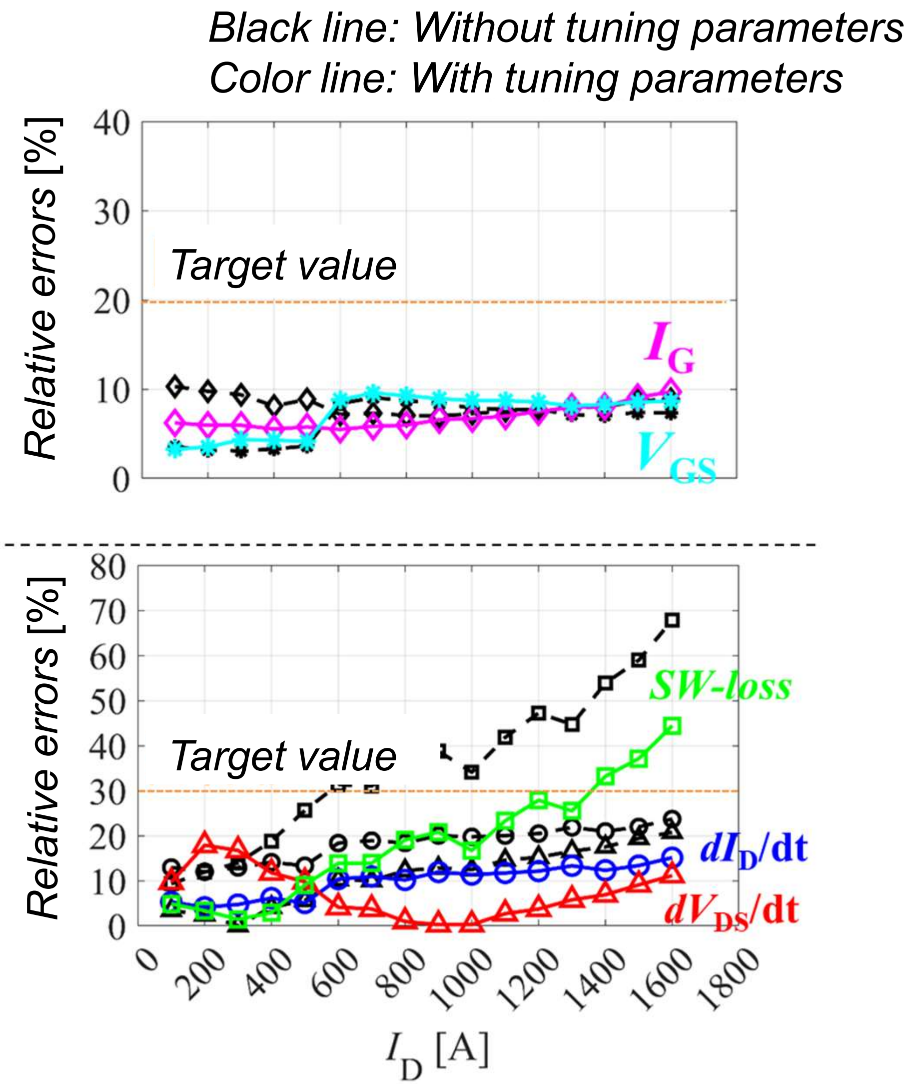
The objective function consists of a total of eight factors that take into account turn-on and turn-off.

$$f_{obj} = I_{G.ON.RMSE} + I_{G.OFF.RMSE} + V_{GS.ON.RMSE} + V_{GS.OFF.RMSE} + \frac{dI_{D.ON}}{dt}_{RMSE} + \frac{dI_{D.OFF}}{dt}_{RMSE} + \frac{dV_{DS.ON}}{dt}_{RMSE} + \frac{dV_{DS.OFF}}{dt}_{RMSE}$$

④The objective function is minimized by simulated annealing.

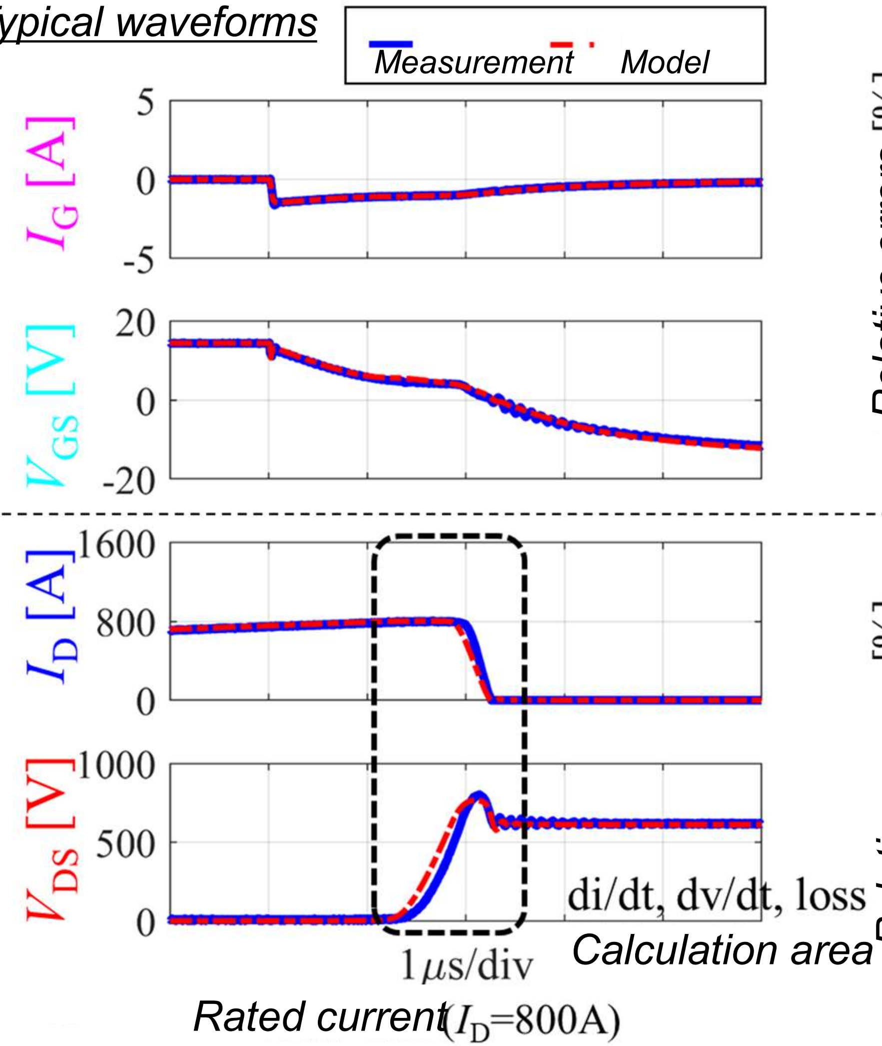
Comparison of measurement and analysis (turn-on)





Comparison of measurement and analysis (turn-off)

Typical waveforms



Black line: Without tuning parameters
Color line: With tuning parameters