TOSHIBA

Technical Review

Front-Loading of EMC and Thermal Design Technologies to Improve Reliability of Automotive Semiconductor Products

In recent years, the dissemination of electric vehicles (EVs) and the development of automated driving technologies have led to an increase in the number of electronic control units (ECUs) installed in automobiles. In order to assure the reliability of these ECUs, there is a need to resolve issues related to the electromagnetic compatibility (EMC) and thermal effects of semiconductor products. An approach to the front-loading of EMC and thermal design technologies is therefore required to reduce the impact of process retrogression and shorten development periods in line with the international trend in the development of next-generation automobiles.

This is the context in which Toshiba Electronic Devices & Storage Corporation has been making efforts to develop front-loading technologies for the EMC and thermal design of automotive semiconductor products. In the field of analog integrated circuits (ICs), we have established development environments that make it possible to improve the accuracy of noise simulations and perform electrothermal circuit simulations taking into consideration the interconnections among devices on an IC. In the field of discrete power devices, we are also developing an electrothermal circuit simulation method for switching applications using power metal-oxide-semiconductor field-effect transistors (MOSFETs).

1.Introduction

With the spread of EVs and automated driving technologies, the number of ECUs in automobiles has increased, exacerbating the difficulty of automotive semiconductor product development. In the face of an accelerating automobile development cycle, design iterations due to EMC and thermal issues are becoming a problem. It is important to harmonize EMC and thermal design conflicts early in the development cycle because there is often a trade-off between EMC and thermal characteristics. This is the context in which Toshiba Electronic Devices & Storage Corporation is committed to front-loading EMC and thermal design efforts.

Accompanying the progress of automated driving, EMC regulations governing automotive electronics have been becoming increasingly important for preventing their malfunction so as to ensure the safety of automobiles. In 2016, compliance with ECE Regulation No. 10 (ECE R10), a vehicle safety regulation established by the United Nations Economic Commission for Europe (UNECE), became mandatory in Japan. Toshiba Electronic Devices & Storage Corporation established the Semiconductor EMC Test Laboratory in 2015, which obtained International Organization for Standardization (ISO) 17025 certification in 2018. Since its establishment, we have endeavored to improve our measurement and evaluation capabilities concerning International Electrotechnical Commission (IEC) and other international standards and utilized those capabilities for product development.

Thermal design is important not only for automotive analog motor driver integrated circuits (ICs) with a 10-A output but also for high-level multicore CPUs in automotive microcontroller units (MCUs). Thermal design is also required for discrete power devices if they are used in an ECU.

Thermal simulation is therefore essential for automotive semiconductor products. Previously, we had employed thermal simulation incorporating chassis and other models for the development of engine control ICs as well as MCUs for advanced driver assistance systems (ADAS). In addition, we have embarked on new initiatives to apply thermal simulation to the development of discrete power devices. This report describes these initiatives.

2. Initiatives for front-loading of EMC analyses

Previously, a probe was used for the EMC fault analysis of automotive ICs. However, the use of a probe made it difficult to obtain an accurate measurement because of the effect of a measuring system. To address this problem, we conducted joint research with the laboratory of Professor Makoto Nagata at Kobe University on EMC(1)(2). In this project, we used on-chip waveform monitors (OCM) to analyze a circuit malfunction by the direct power injection (DPI) method, a method of testing a circuit's electromagnetic susceptibility (EMS). Consequently, we have verified EMC phenomena and fed back the research results to circuit simulation. OCMs are electronic probes that are integrated on-chip to monitor circuit waveforms with minimal effects of circuit characteristics and IC layout.

Figure 1 schematically shows how DPI noise propagates from a double-diffused metal oxide semiconductor (DMOS) to a silicon (Si) substrate. As shown in Figure 1, noise propagates to circuit elements through IC pins and metal layers, acting as a major cause of a circuit malfunction.

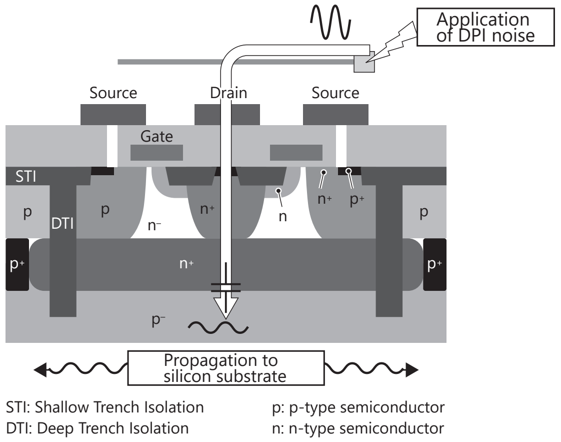


Figure 1. Propagation of DPI noise from double-diff used MOS (DMOS) to silicon substrate

DPI noise propagates from the DMOS output stage to the IC pins, metal layers, and silicon substrate and then flows to other elements, causing a malfunction.

For the joint research, we have developed a test element group (TEG) consisting of OCMs, a Local Interconnect Network (LIN) transceiver, and a Controller Area Network (CAN) transceiver, fabricated with an automotive 0.13-µm BiCD (bipolar + complementary MOS (CMOS) + DMOS) (40V) process (**Figure 2**). This OCM TEG is capable of observing changes in voltage between 0 V and 40 V at internal circuit nodes and the Si substrate, including changes in frequency and phase.

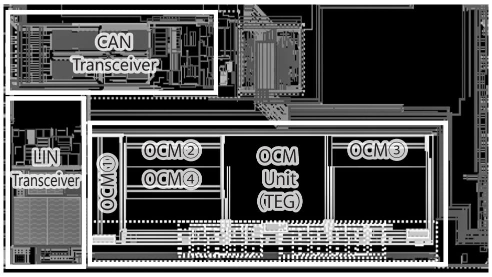
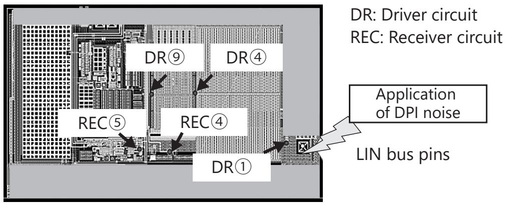


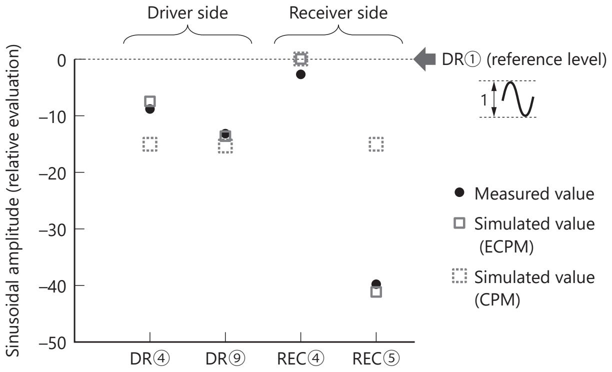
Figure 2. Block diagram of OCM TEG

The OCM TEG is designed to measure changes in the voltage of internal circuit nodes and Si substrate caused by the application of DPI noise. It comprises LIN transceiver, CAN transceiver, and OCM blocks.

Figure 3 shows an example of the placement of OCMs in an LIN transceiver and compares the DPI noise levels measured by these OCMs with those simulated by a noise analysis and verification tool. Based on the results of research conducted at the laboratory of Professor Nagata, a nonlinear extended chip power model (ECPM) incorporating protection diodes has been added to a linear chip power model (CPM) that was previously used for EMC analysis. Consequently, we have succeeded in matching the results of simulation with the DPI noise levels measured by each OCM according to the distance from the Si substrate and the type of peripheral devices.



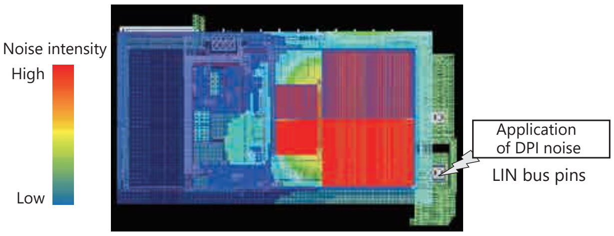
(a) OCM placement in LIN transceiver



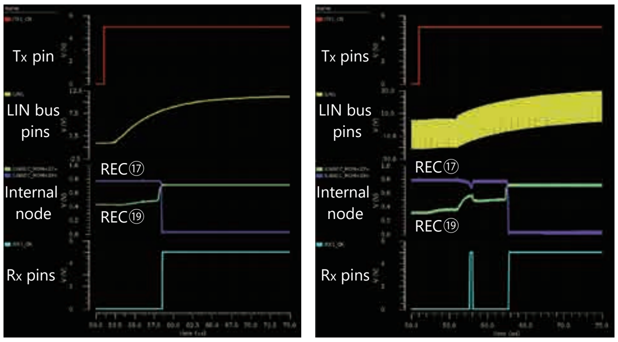
(b) Comparison of measured and simulated values of DPI noise level

Figure 3. Comparison of measured and simulated values of DPI noise level at each location of OCM in LIN transceiver

The LIN transceiver incorporates five OCMs. The measured and simulated values of the DPI noise level almost matched at all OCMs.



(a) DPI noise level distribution



Without DPI noise application With DPI noise application

(b) Results of simulations

Figure 4. Results of simulations of DPI noise level distribution and waveform data with and without DPI noise application of LIN transceiver

A simulation shows that the application of DPI noise causes a malfunction of internal nodes, generating a false pulse at the R_x pin.

Figure 4(a) is the result of a simulation of DPI noise application to the LIN transceiver, which shows the distribution of the intensity of DPI noise applied from the LIN bus pins at the lower right portion of the chip (with the red color being most intense and the blue color being least intense). Figure 4(b) shows the results of simulations with and without DPI noise application. When DPI noise was applied to the LIN bus pins that operate with a signal from the input pin (T_x), the internal nodes malfunctioned, causing a false pulse to appear at the output pin (R_x). The results of this simulation and OCM measurements matched.

The improvement in the accuracy of simulation with DPI noise application makes it possible to estimate DPI noise immunity in advance in accordance with the IEC 62132-4 standard using circuit, layout, package, and other data, enabling the front-loading of an EMC analysis. The newly developed technology can also be used to analyze internal noise in an IC. At present, we are using this technology for fault verification of DC (Direct Current)-DC converters and high-current motor drivers since it is capable of identifying victim devices that are affected by noise from aggressor devices.

We are currently developing CAN-FD (CAN with Flexible Data Rate), LIN, and Clock Extension Peripheral Interface (CXPI) transceivers using this technology.

3. Initiatives for front-loading of thermal design

3.1 Electrothermal simulation of BiCD process

For the 0.13-µm BiCD process, we had already employed transient thermal simulation, incorporating package, printed circuit board (PCB), heatsink, and chassis data. In addition, we have realized simulation of thermally modeled devices that affect one another.

Examples of thermal equivalent circuit models are shown in **Figure 5**. A self-heating model was added to the SPICE (Simulation Program with Integrated Circuit Emphasis) models of the DMOS output stage (M1A and M1B) and the small-signal block whereas thermal conduction models were added between the DMOS output stage and the small-signal block. Typical SPICE simulations cannot simulate changes in electrical characteristics over time because a circuit's electrical characteristics are analyzed while keeping junction temperature (T_j) constant, for example, at 125°C. However, the addition of the thermal model (self-heating or thermal conduction model) made it possible to simulate changes in electrical characteristics that cause a transient increase in temperature in a DMOS die because of self-heating in high-current applications.

Figure 6 shows the results of electrothermal SPICE simulation, including the DMOS output waveforms. The device temperature increased gradually as it increased and decreased repeatedly while a DMOS turned on and off with a pulse-width-modulation (PWM) signal. The output current also decreased over time because of self-heating while DMOS was on whereas the current consumption in the small-signal block slightly decreased over time.

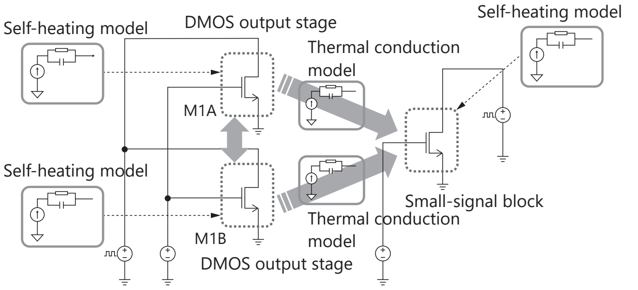
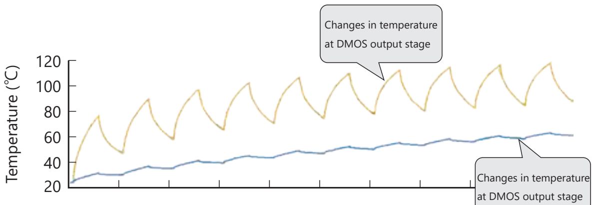
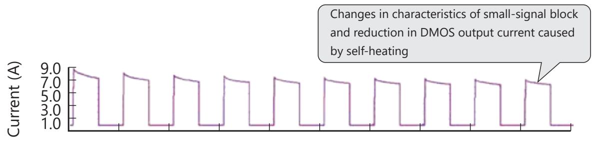


Figure 5. Thermal equivalent circuit model added to devices in IC

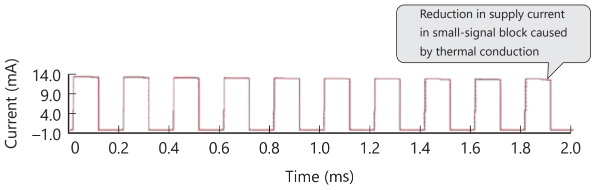
Thermal equivalent circuit models (self-heating and thermal conduction models) were added to the SPICE models of the DMOS output stage, the small-signal block, and other devices.



(a) Device temperature



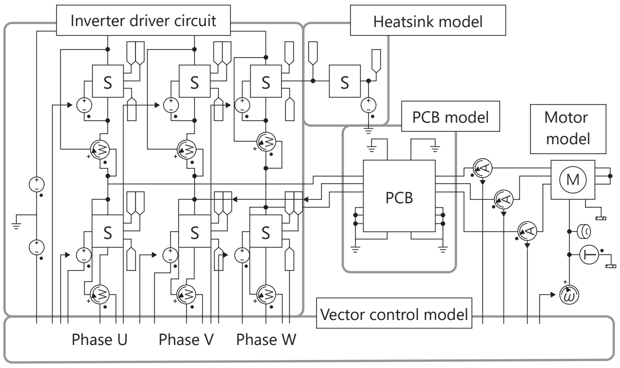
(b) DMOS output current



(c) Supply current in small-signal block

Figure 6. Results of electrothermal circuit simulations

Electrothermal circuit simulations were performed to evaluate device temperature, DMOS output current, and the current consumption in the small-signal block using the SPICE models shown in Figure 5.



S: SPICE model A: Ammeter T: Thermometer M: Motor ω: Phase meter W: Wattmeter

Figure 7. Electrothermal circuit simulation model for three-phase brushless motor driver using MOSFETs

The electrothermally simulated circuit block comprises a vector control model, a PCB model, an inverter driver circuit, a heatsink model, and a motor model. Thermal models were added to the SPICE models of power MOSFETs in the inverter driver circuit.

3.2 Electrothermal simulation of discrete power devices

We performed an electrothermal simulation of discrete power devices to achieve front-loading of ECU development.

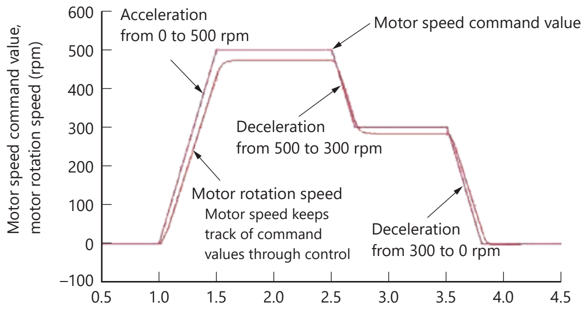
This subsection describes an example of application of electrothermal simulation to an inverter for three-phase brushless motors.

Figure 7 shows an example of an electrothermal simulation of a system that consists of SPICE and thermal models using a multi-domain electronic design automation (EDA) tool.

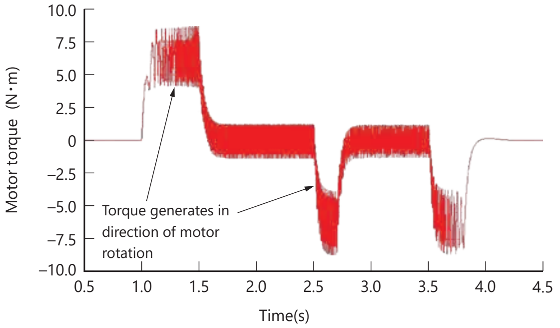
Thermal models were added to the SPICE models of the power MOS field-effect transistors (MOSFETs) in the inverter driver circuit for three-phase brushless motors(3)(4) so as to enable a simulation of self-heating. Vector control, PCB, heatsink, and motor models were written using a multi-domain tool.

Figure 8 shows the measured changes in the parameters of a motor over time using this inverter driver circuit. Figure 8(a) shows motor speed command values vs. motor rotation speed. The motor speed was increased from 0 rpm to 500 rpm and then decreased from 500 rpm to 300 rpm and from 300 rpm to 0 rpm. Figure 8(b) shows the resulting motor torque waveform. The torque increased in the positive direction as the motor speed increased whereas the torque increased in the negative direction as the motor speed decreased. As shown in Figure 8(c), the motor current increased (in Phase U, Phase V, and Phase W) as the torque increased whereas the motor current decreased as the torque decreased. Figure 8(d) shows that as the motor current increased and decreased, T_j of all the high-side and low-side power MOSFETs (of Phase U, Phase V, and Phase W) changed because of the transient heat generated by the drain current of each MOSFET. While the motor current was flowing, the values of MOSFET thermal characteristics increased because of self-heating. It is therefore possible to optimize heatsinks and other thermal pathways of a chassis by taking these thermal characteristics into consideration.

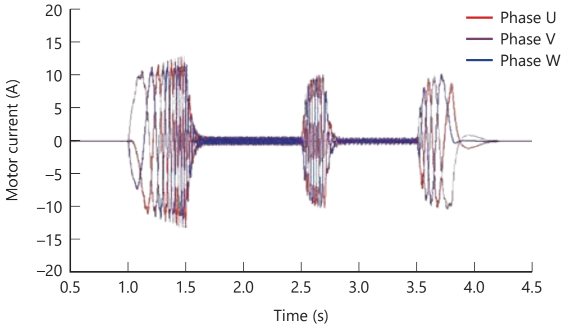
The technologies described above greatly help reduce iterations of the development cycle. We will further improve these technologies to reduce the simulation workload so that our customers can easily perform electrothermal simulations.



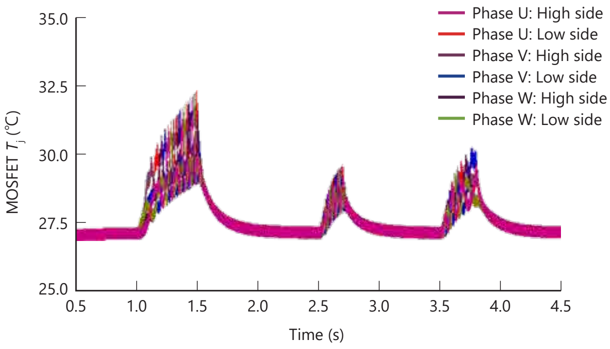
(a) Motor speed command value vs. motor rotation speed



(b) Motor torque waveform



(c) Motor current



(d) MOSFET T_j

Figure 8. Results obtained by simulations of motor driving parameter and MOSFET T_j changes over time

The motor rotational speed, motor torque, motor current, and MOSFET T_j waveforms changed over time according to motor speed command values.

4. Conclusion

We have established a development environment for the front-loading of EMC and thermal design for automotive analog ICs. At present, we are developing front-loading technologies for discrete power devices. We will continue to develop techniques for further reducing simulation time so as to contribute to our customers' ECU development.

References

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