Dynamic Characteristics Analysis of 3,300 V Full SiC Power Module by New Equivalent Circuit

Satoshi HATSUKAWA*, Shigenori TOYOSHIMA, Takashi TSUNO and Yasuki MIKAMURA

Silicon Carbide (SiC) devices are promising candidates for high power, high speed, and high temperature switches owing to their superior properties. We have been developing SiC based 3,300 V class metal-oxide-semiconductor field-effect transistors (MOSFETs) and schottky-barrier diodes (SBDs). Stray inductance in the module and the great current changing rate with high speed switching may cause excessive voltage overshooting. Although equivalent circuits are effective for stray inductance analysis, previous equivalent circuit studies covered only a partial area of the entire module. This paper proposes a new method for the dynamic characteristics analysis using the precise equivalent circuit of the entire module.

Keywords: SiC MOSFET, SiC SBD, SiC power module, low inductance, equivalent circuit

1. Introduction

Reflecting significantly growing international concern regarding global warming, the need to reduce CO_2 emissions has been widely recognized. In parallel with this, the development of energy-saving technology is regarded as an important measure for coping with the approaching depletion of oil and other fossil fuel resources. Electric energy is a very convenient form of energy and is increasing its proportion of total energy year by year. Therefore, the development of technology that will enable efficient use of electric energy is positioned as an important pillar toward effective energy conservation. Electric power energy is converted to various forms before it is consumed by end users. Semiconductor devices or power devices used in electric power equipment play a key role in converting electric energy to other forms. User demand for the development of power devices with high energy-saving performance has been increasing recently.

Similarly to ordinary semiconductors, most currently available high voltage, high current, high speed/high frequency power devices are formed on silicon (Si) substrates. Regarding Si-based power devices, metal-oxide-semiconductor field-effect transistors, insulated gate bipolar transistors, and other devices have been developed and their uses for power conversion are expanding. However, these devices are reaching their performance limits, which are determined theoretically by their dielectric breakdown field, electron saturation velocity, and other physical properties. The development of high performance power devices made from a new semiconductor material other than Si is desirable.

One of the new promising semiconductor materials is silicon carbide (SiC), which is a wide band gap semiconductor material. SiC has been previously used as an abrasive or heat dissipation material. However, the success in developing a high quality single crystal SiC has intensified research on the use of SiC as a semiconductor. SiC is a promising power device material as it has a higher dielectric breakdown field, electron saturation velocity, and thermal conductivity than Si. Research and development of SiC-based high blocking voltage, high speed, low on resistance power devices has been energetically carried out.[(1)-(3)]

Following the commercialization of a SiC Schottky diode, the development of other types of switching devices, a vertical metal-oxide-semiconductor field-effect transistors (MOSFET) in particular, has been energetically pursued. A vertical MOSFET is highly expected as a high current, high voltage device. The vertical MOSFET has the same structure as that of Si MOSFETs and it can be made by the same process as that for Si MOSFETs.

The authors have developed a SiC power module having a withstand voltage of 3,300 V and a current capacity of 400 A, and confirmed that it has a superior switching characteristic.[(4)] Stray inductance in the module and an increase in current change rate attributed to fast switching may cause excessive voltage overshooting.

As a device that can prevent such voltage overshooting, we have also developed a 1,200 V, 100 A low inductance SiC power module.[(5)] To reduce the stray inductance of the newly developed 3,300 V, 400 A SiC power module, we analyzed the stray inductance of this module. Although it is effective to analyze stray inductance by representing the power module by its equivalent circuit, previously known analysis method used an equivalent circuit that was expressed by only the representative value of the elements and inductance of the power module. We have developed a new method for creating an equivalent circuit that can express every element of the module, and confirmed that the new method reproduces actual measured values at high accuracy. This paper describes and discusses the newly developed analysis method and the results obtained by the method.

2. New Model of SiC Power Module

A photo of the newly developed 3,300 V, 400 A SiC power module is shown in Fig. 1. For inverter application, this power module is made as a 2 in 1 module consisting of a high voltage arm (D1-S1) and low voltage arm (D2-S2).

The forward ON characteristic of one arm is shown in Fig. 2. This figure shows that the rated current of 400 A flows when the gate voltage (V_{GS}) is 20 V and the drain voltage (V_{DS}) is 2 V. The internal structure of the power module is shown in Fig. 3. Six SiC MOSFET chips and six SiC schottky-barrier diode (SBD) chips are mounted on a single substrate so that two substrates constitute one arm and two arms constitute a 2 in 1 module. Twelve SiC MOSFETs and twelve SiC SBDs are arranged in parallel for each arm.

The equivalent circuit of a previous module is shown in Fig. 4. The SiC MOSFET, SiC SBD, and stray inductance are each illustrated integrally by their respective representative models.

When we developed the new equivalent circuit, we first determined the simulation program with integrated circuit emphasis (SPICE)*[1] model of each of the SiC MOSFET and SiC SBD chips. Using an NMOS model for the SiC MOSFET and a D model for the SBD, we manually adjusted the parameters of these models so that the calculation would agree well with the actual measurement. The calculated values and actual measured values of the forward characteristics of a single chip of the SiC MOSFET and SBD were compared. The results are shown in Fig. 5. The figure verifies that the calculation can accurately simulate the actual measurement. To express the

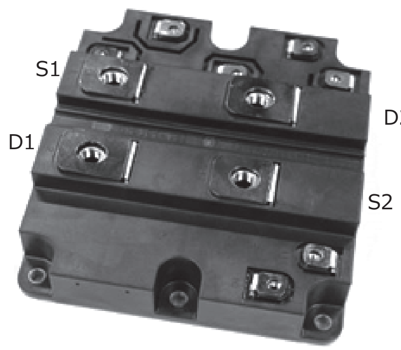


Fig. 1. 3,300 V, 400 A 2 in 1 SiC power module (130 x 140 mm[2])

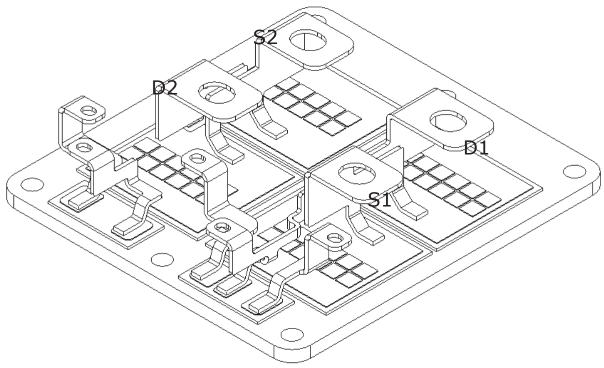


Fig. 3. Internal structure of 3,300 V, 400 A SiC power module

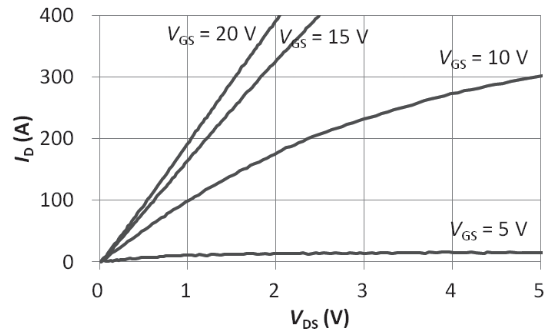


Fig. 2. I_D-V_{DS} forward characteristics of 3,300 V, 400 A SiC power module

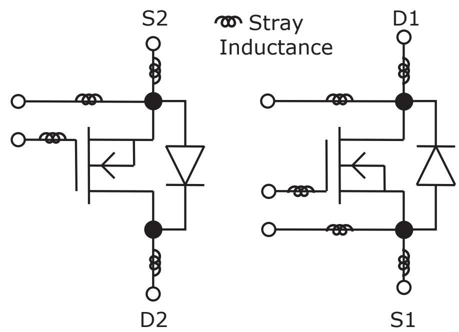


Fig. 4. Equivalent circuit of a previous module

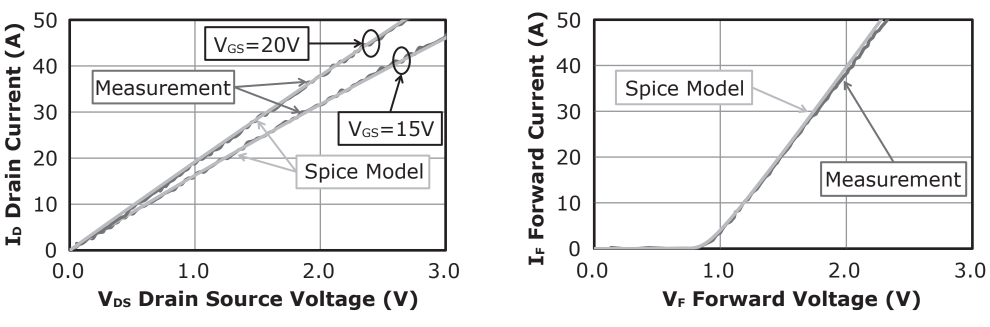


Fig. 5. Comparison between calculation and actual measurement of forward characteristics

stray inductance of terminals, circuits on the substrate, bonded wires, and other conductors by an equivalent circuit, we used the ANSYS Q3D Extractor.

We created an equivalent circuit of the inner portion of the module by combining the equivalent circuits of the SiC MOSFET model, SiC SBD model, and stray inductance. Part of the equivalent circuit is shown in Fig. 6.

Figure 6 shows six SiC MOSFET chips, six SBD chips, and their inductance circuits on a single substrate. The mutual inductance between the inductance circuits is not shown in this figure. When the equivalent circuit created above was calculated on the LTspice IV, the calculated values contained large errors or the calculation required a considerably long period of time. The reason for such large errors was that the equivalent circuit of the inductance was complex and made the calculations cumbersome and complicated. To enhance the calculation efficiency, we developed a new program that can efficiently create the equivalent circuit of inductance by omitting less influential inductance.

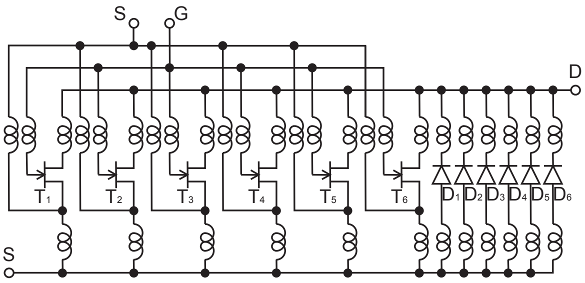


Fig. 6. Equivalent circuit of module (for a single substrate)

Combined use of a new equivalent inductance circuit with the equivalent circuits of the SiC MOSFET and SBD chips has enabled the elimination of calculation errors and analysis of the characteristics of power devices within a short period of time.

An electromagnetic field analysis was previously required to simulate the dynamic characteristics of a power module. The newly developed analysis method enables the same simulation within about one-tenth time.

3. Evaluation of SiC Power Module Model

The circuit that we used to evaluate the dynamic characteristics of SiC power modules is shown in Fig. 7. For the evaluation, we applied a 100 μH reactance load to the specimen at room temperature. The dynamic characteristics waveforms at a voltage of 1,650 V are shown in Fig. 8.

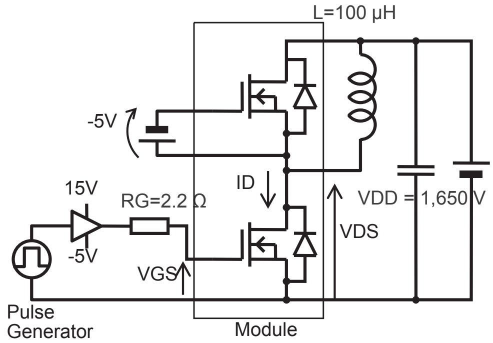
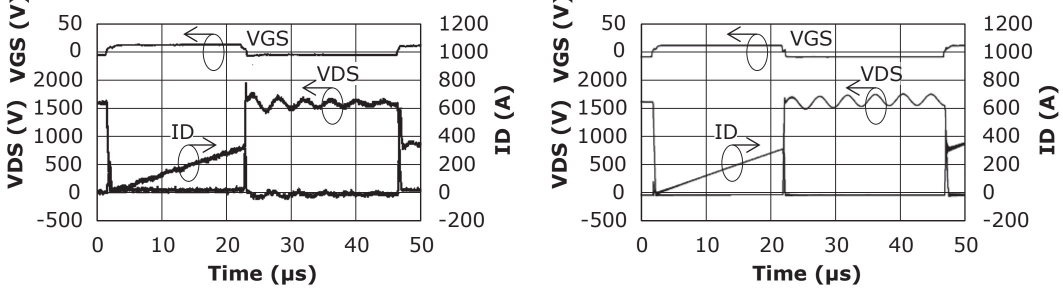


Fig. 7. Dynamic characteristics evaluation circuit

Figure 8 (a) shows the actual measured waveforms, while Fig. 8 (b) shows the waveforms of a SiC power module that were calculated using LTspice IV. The actually measured rise time tr and fall time tf were 404 ns and 238 ns, respectively, while the calculated tr and tf were 402 ns and 226 ns, respectively. Thus the calculation agreed quite well with the actual measurement. The calculated resonance frequency of V_{DS}, which was 23.2 kHz, also agreed well with the actual measured value, which was 22.5 kHz.

We also calculated the voltage and current of each SiC chip that constituted the power module. As shown in Fig. 9, the arm on the operation side of this module comprised near side and far side substrates when viewed from the sub terminals. Calculation results of the turn-on time and turn-off time dynamic characteristics are shown in Fig. 10 (a) and (b), respectively. These figures show that voltage V_{DS} was the same between individual chips, while current I_D was larger on the near side than the far side. In particular, turn-on time current overshooting occurred on the near side. The maximum overshooting current of nearly 90 A was measured in the N4 chip.



(a) Actually measured waveforms (b) Waveforms calculated using model

Fig. 8. Comparison of dynamic characteristics waveforms (switching of inductance load at power source voltage of 1,650 V)

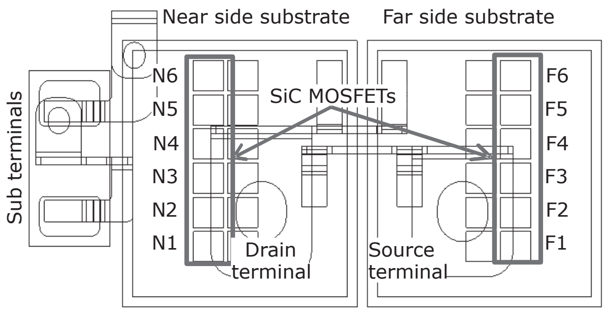


Fig. 9. Chip layout for one arm

We concluded that the current was larger on the near side than on the far side because the gate voltage V_{GS} was larger on the near side than on the far side as shown in Fig. 10, and this difference in gate voltage created a difference in the on resistance of the MOSFET, leading to a difference in current. We also concluded that current overshooting occurred on the near side because the inductance of the gate circuit on the far side delayed signals and concentrated the current on only the near side.

Based on the above analytical study results, we will modify the substrate wiring so that the gate signal will reach each chip at the same time.

4. Conclusion

The authors have developed an equivalent circuit of the 3,300 V, 400 A SiC power module, and confirmed that the new equivalent circuit can simulate the actual waveforms of the module.

In the future, we will use this new equivalent circuit model to optimize the current distribution in the module and thereby design a low inductance module that will not produce current overshooting or any other abnormal waveform.

• Q3D Extractor is a trademark of ANSYS Corp.
• LTspice is a trademark of Linear Technology Corp.

Technical Term

＊1 Simulation program with integrated circuit emphasis (SPICE): An analog electronic circuit simulation program developed in 1973 by the University of California, Berkeley.

References

(1) M. Bhatnagar, B.J. Baliga, IEEE Trans. Electron Devices, 40 (1993) 645-655
(2) Z. Stum, A.V. Bolotnikov, et al., Mater. Sci. Forum., 679-680 (2011) 637-640
(3) A. Bolotnikov, P. Losee, et al., in Proc. ISPSD (2012) 389-392
(4) Y. Saitoh, T. Hiyoshi, K. Wada, T. Masuda, T. Tsuno and Y. Mikamura, SEI Technical Review, No. 80, pp. 75-80 (2015)
(5) S. Toyoshima, S. Hatsukawa, N. Hirakata, T. Tsuno, Y. Mikamura, SEI Technical Review, No. 80, pp. 81-84 (2015)

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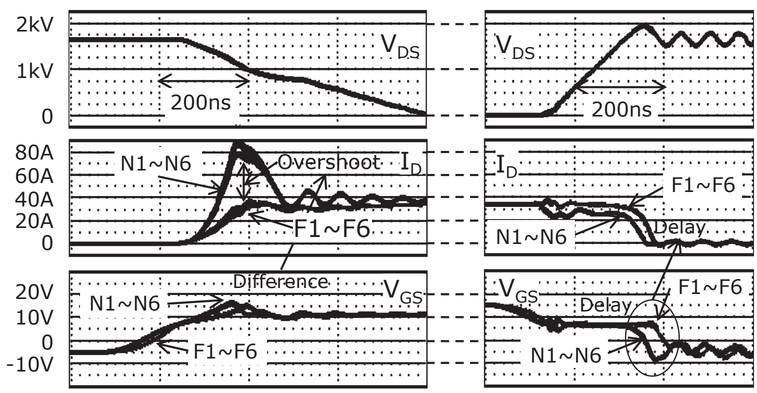

(a) Turn-on time (b) Turn-off time

Fig. 10. Calculated switching waveform of each chip current (power source voltage: 1,650 V)