Technology Explanation

Thermal Analysis of Electronic Circuits

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Abstract

In recent years, due to the "CASE (Connected, Autonomous, Shared, Electric)" technological trend, electronic control units (ECUs) need to be installed at free locations and they need to realize higher performance, have more electronic capabilities, high-density packaging, and integrate multiple functionalities. These requirements crowd heat-generating components and accelerate deterioration. On the other hand, consumer electronic devices such as smartphones are progressing in their complexity and downsizing. These are achieved by saving power through high-performance semiconductors and improving the heat dissipation structure. The thermal design is important to achieve similar performance in ECU. The thermal design makes it possible to secure the required service life, performance, and quality by predicting temperature and dissipating heat, while pursuing the limit of heat generation density. Generally, computational fluid dynamics, which is 3D simulation, is used for the prediction of temperature. However, it is effective to repeat the thermal network method, which is 1D simulation, to verify the feasibility in the upstream area of development flow to prevent rework from the downstream area. This paper reports on detailed modeling to confirm heat phenomena of the electronic circuit and discuss the results of 1D simulation which is accurate and fast.

1 Introduction

In designing Electronic Control Units(ECU) to satisfy upcoming needs for a wide range of high-end applications like automotive or construction machines, it has recently become more important to address thermal issues. In these applications, only limited space is available for such electronic components and the trend of motorization and electronification results in higher power consumption. Naturally, the electronic components reach higher temperatures by internally generating heat, accelerating the deterioration of mounted chips. The trend of in-vehicle electronics packaging technology is shown in Fig. 1:

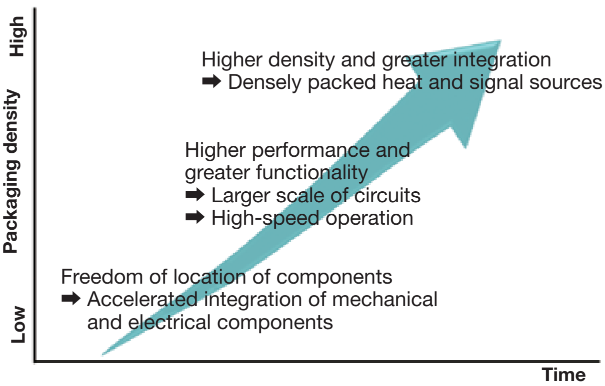


Fig. 1 Trend of ECU packaging technology

To guarantee the service life of products, it is necessary to reduce heat generation through power saving and to lower the temperature by raising the heat dissipation capability. Finer digital circuits have contributed to power saving in such a remarkable way that their processing capability has been doubled in two years while retaining the same power consumption. With the emergence of compound semiconductors such as silicon carbide (SiC) and gallium nitride (GaN), power devices have been downsized with higher switching efficiency and higher switching frequency. Their heat dissipation capacity has also been enhanced. With improved electronics packages and advanced heat transfer materials, today's electronics can be designed to release heat into the atmosphere via their cases to prevent the build-up of heat inside.

Electronics designers need to pursue the limitation of heat generation density in order to improve product competitiveness. Downsizing a product will always decrease its weight, resulting in lower cost. However, the product may also have a higher internal temperature which exceeds the specified service temperature limit or shortens the service life of the components mounted therein. Therefore, it is indispensable to properly estimate the size, weight, cost, life, and quality in the upstream stage of product development.

This paper briefly explains some of our engineering challenges we have continuously addressed in relation to the above-described estimations. Specifically, with a focus placed on the thermal network method, which replaces heat transfer with an equivalent electric circuit, the following describes an analysis approach using an electronic circuit simulator for calculation.

2 Service Life of Electronic Components

One of the major factors that reduce the service life (Hereafter, service life is represented by life) of electronic components is thermal fatigue. Electronic components may experience failure when a thermal chemical reaction reaches a limit [1)].

To predict the life, an acceleration test using the Arrhenius equation (Equation (1)) to predict the chemical reaction speed K at a certain temperature T is widely used:

$$K = A\exp\left(-\frac{E_a}{kT}\right) \tag{1}$$

A: Constant
E_a: Activated energy [J]
k: Boltzmann's constant [J/K]

When the time (life) for product to have a failure at temperatures T_1 and T_2 is L_1 and L_2 respectively, Equation (2) below can be obtained:

$$\ln L_1 - \ln L_2 = \frac{E_a}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right) \tag{2}$$

Accordingly, the natural logarithm of the life that was actually measured during the acceleration test is proportional to the plotted inverse of the temperature. This linear relationship is called the Arrhenius plot (Fig. 2). The slope of the line can be used to determine the activated energy E_a. Giving the combined setting of operating temperature and time (temperature profile) of the component as shown in Table 1 enables prediction of the life.

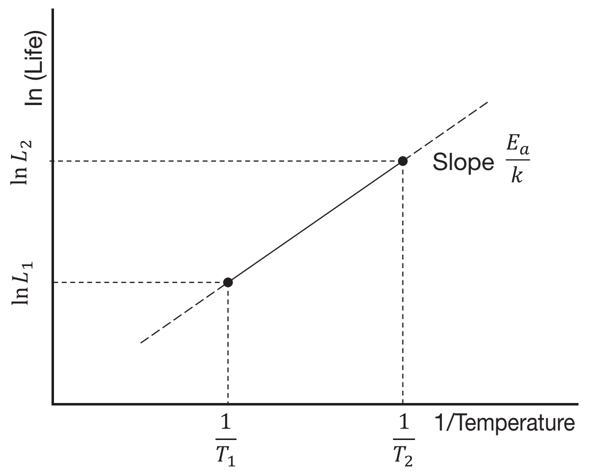


Fig. 2 Arrhenius plot diagram

Table 1 Example of temperature profile

State	Per day				Per 15 years
	tj (°C)	Time (h/day)	150°C-equivalent time (h/day)	Rate (%)	150°C-equivalent time (h)
Active	130	0.05	0.01924	11.00	105
	100	0.95	0.07203	41.17	395
	70	7.00	0.07870	44.98	431
Inactive	25	16.00	0.00500	2.86	27
Total			0.17497	100.00	959
Upper limit			0.18252	100.00	1000

3 Heat Generated by ECUs

The dominant heat generated by an electric control unit (ECU) is Joule heat from the packaged electronic components. This heat is transferred to the ECU casing via the printed circuit board (PCB) and then released into the atmosphere (Fig. 3). This section explains how the heat is transferred with a focus on the PCB, which can efficiently transfer the heat from the electronic component as a heat source.

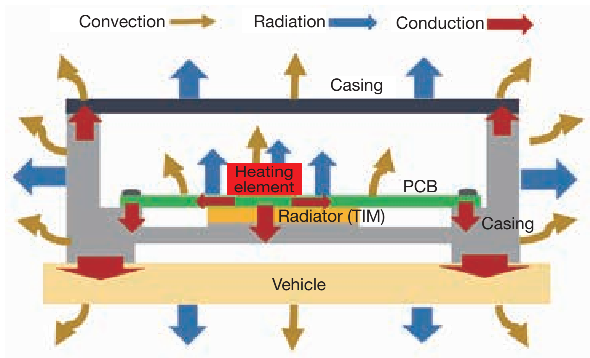


Fig. 3 Heat path of ECU

Once the heat consumption P from the heat source, the atmospheric temperature T_a, and the thermal resistance θ determining how the heat is transferred have been determined, the heat source temperature T can be estimated by Equation (3):

$$T = T_a + \theta P \tag{3}$$

where θ is the total thermal resistance of all heat dissipation paths between the heat source and the atmosphere. In reality, it is complex to calculate the heat source temperature due to the existence of two or more heat sources, two or more heat paths, and the temperature distribution of the atmosphere (Fig. 4). Still, it is possible to determine the heat source temperature simply by determining the thermal resistance of the relevant parts.

When the amount of heat of the heating component and the thermal resistance of the PCB in releasing the heat to the atmosphere are known, the area of the PCB with the required heat dissipation capability can be determined. Since the heat consumption of the electronic component as a heat source depends on the temperature, it is necessary to use a simulation tool that can support the electric and thermal calculations as a pair.

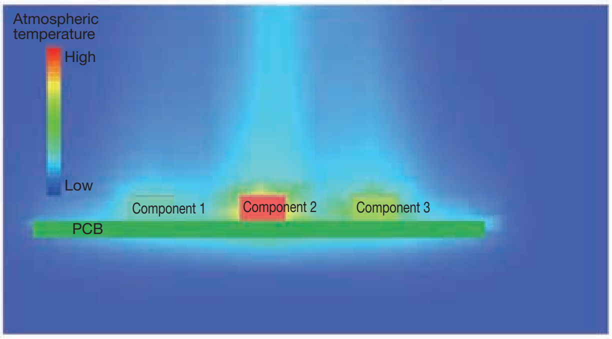


Fig. 4 Heat dissipation to atmosphere

4 Simulation Tool

Thermal analysis is often carried out using dedicated thermal fluid analysis tools. In the conceptual design stage in the upstream stage of product development, where more importance is placed on "guessing," however, it is desirable to carry out a one-dimensional (1D) simulation, not the thermal fluid analysis or another simulation using three-dimensional (3D) profile models. The 1D simulation referred to herein means to replace the heat dissipation path with a thermal network to allow repetitive simulation under variable conditions [2)].

What is important in the process of thermal network calculation is the heat consumption of electronic components and the thermal resistance of the heat dissipation path. Conventionally, the heat consumption has been estimated from the standard values included in the data sheets, but depending on the conditions, in some cases the estimation obtained in this method was quite different from the actual heat consumption. This is because the heat consumption of electronic components varies by temperature due to the variations further depending on the manufacturing dispersion of electronic components, and because different electronic components affect each other, resulting in changes in temperature. A solution is to analyze the two kinds of phenomena, namely electric and thermal, along with their interactions.

It may be possible to carry out this analysis through theoretical calculation, but the calculation must be repeated many times. Thus, it is more efficient to use a simulator. For 1D simulation of electronic circuits, we use a simulation tool based on Simulation Program with Integrated Circuit Emphasis (SPICE), which is widely used nowadays. The use of SPICE makes it possible to carry out the simultaneous simulation of both electronic and thermal circuits.

Recently, electronics manufacturers have been providing thermal models for SPICE in some cases. However, thermal analysis requires thermal models of the majority of heat dissipating paths including PCBs and atmosphere to be prepared. The SPICE-based simulators simply calculate any circuits given; thus, they may fail to produce accurate results if an electric or thermal model with poor accuracy is included. Accordingly, it is important to evaluate the prepared circuits and thermal models and then determine the analysis accuracy.

For electric models, electric characteristics should be determined, and depending on the operating conditions, it may be necessary to adjust with consideration given to the effect of temperature.

The shorter time it takes to complete analysis, the better it is. The model representation method depends on whether the temperature is changing over time (transient state) or is stable after an elapse of sufficient time (steady state). Thus, it is necessary to prepare electric and thermal models suitable for the purpose.

5 Thermal Model of Electronic Components

This section discusses a thermal model of the electronic component shown in Fig. 5. The electronic package internally consists of a semiconductor as a heat source and a package material covering the semiconductor as shown in Fig. 6.

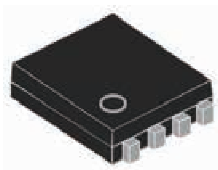


Fig. 5 Semiconductor package

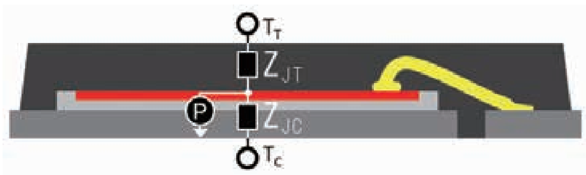


Fig. 6 Internal structure of package

In Fig. 6, P is the heat source, T_T the temperature of the top surface of the package, Z_{JT} the thermal impedance from the p-n junction, colored in red, to the top surface of the package, T_C the temperature of the lower surface (case) of the package, and Z_{JC} the thermal impedance from the p-n junction to the case.

The thermal impedance is the ratio between temperature and heat flow, indicating the resistance of heat to flow in the thermal circuit. There are two types of thermal impedance: resistive and capacitive. These can be represented by the resistance and capacity symbols to form a thermal model of the ladder-type network as shown in Fig. 7(A):

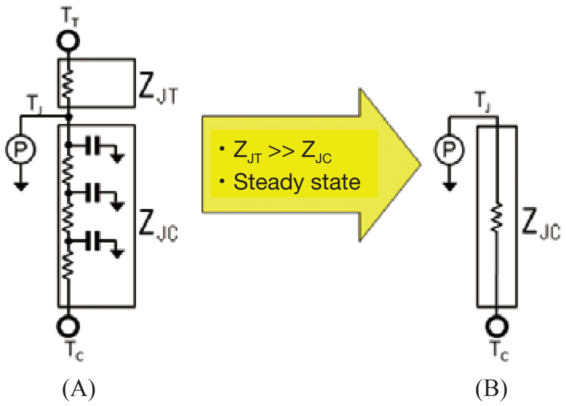


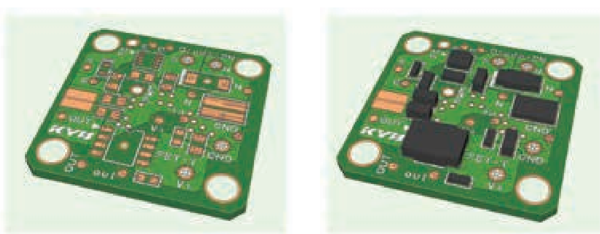
Fig. 7 Thermal model (ladder-type network)

In the steady state, the effect of thermal capacity is negligible. In this example, the network can be simplified into a thermal network only with a thermal resistance shown in Fig. 7(B). The heat consumption P is decided by the power consumption of the devices contained in the package and can be determined from the voltage and current.

If there is any difference between the calculation results and measurements, the model should be modified to improve the analysis accuracy.

5.1 Printed Circuit Boards

The heat generated by electronic components is released into the atmosphere via the PCB (Fig. 8). The thermal resistance of the PCB can be determined from its profile and the thermal conductivity (Table 2) and then can be used as a parameter [3]. The thermal resistance between the PCB and the atmosphere can be determined from the heat transfer coefficient and the surface area of the PCB (Fig. 9).



Bare PCB　　Populated PCB

Fig. 8 PCB

Table 2 Thermal conductivity of PCB materials

Material	Thermal conductivity [W/(m·K)]
Copper	390
Substrate	0.35

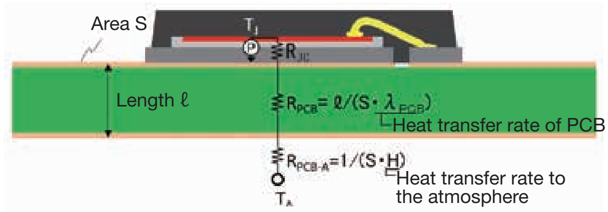


Fig. 9 Thermal model of PCB

5.2 Resistors

When a resistor has a resistance value R, its heat consumption P can be determined by Equation (4) if the current I or voltage V is given:

$$P = VI = \frac{V^2}{R} = RI^2 \tag{4}$$

Multiplying this heat consumption P by the thermal resistance θ of the package material of the resistor will give the temperature difference according to Equation (3), from which the surface temperature of the component can be determined. Electric and thermal models of the resistor are shown in Fig. 10:

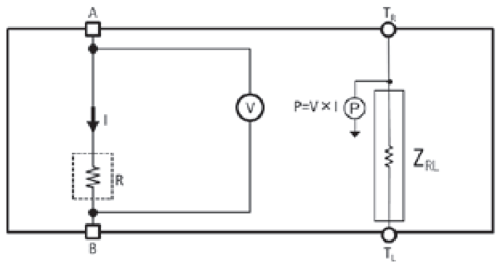


Fig. 10 Electric and thermal models of resistor

5.3 Diodes

A diode is a semiconductor component with two terminals: an anode and a cathode. It conducts current only in one direction, namely from the anode to the cathode, not vice versa.

Diode manufacturers provide SPICE-based thermal models. Using these models, we carried out an electronic circuit simulation and compared the results with the characteristics indicated in the data sheet (Fig. 11).

The diode used for this evaluation has a maximum forward current I_F of 1 A. An electric model is needed to estimate the heat consumption in this region. Since the electric model provided by the manufacturer has a large deviation at a temperature of 125°C, we decided to adjust the model accordingly (Fig. 12).

This task was difficult to achieve only by adjusting the parameters of the electric model. Accordingly, by using a combination of original mathematical expressions, we adjusted the model to attain an average error of around 10%. To reduce the calculation load, the model has been simplified except for a current region around 1 A, where accuracy is required.

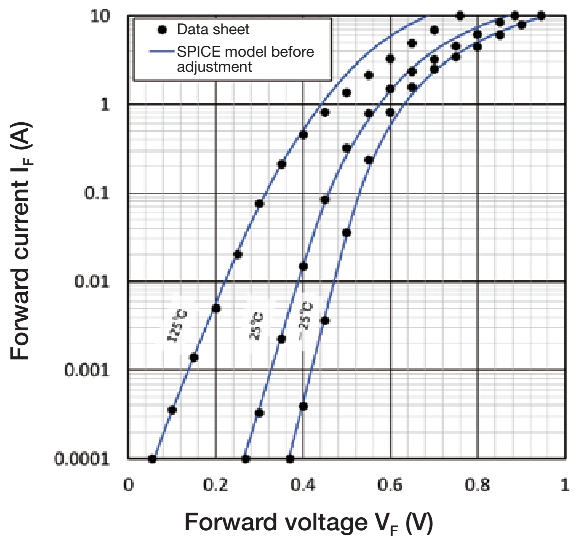


Fig. 11 I_F-V_F characteristics of diode

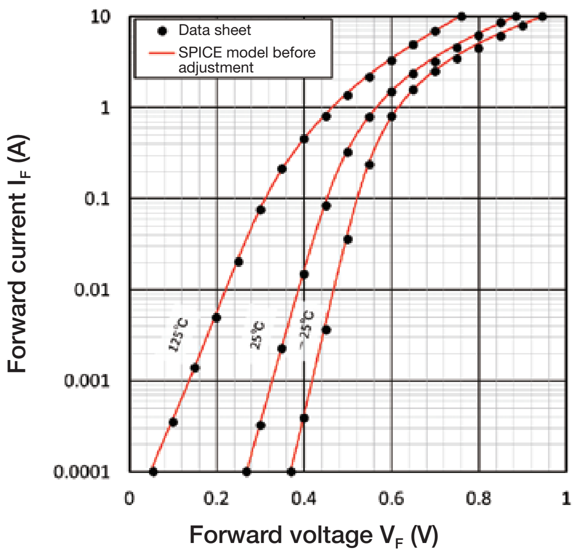


Fig. 12 I_F-V_F characteristics of adjusted diode

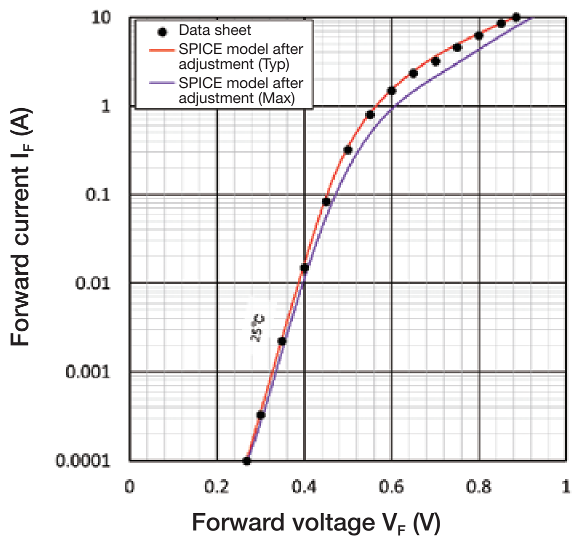


Fig. 13 I_F-V_F characteristics of diode with highest heat consumption

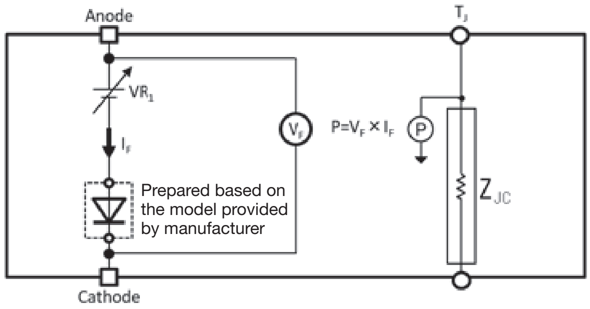


Fig. 14 Electric and thermal models of diode

The manufacturing dispersion of semiconductors affects how likely they are to generate heat. In consideration of that, we continuously think about the satisfied circuit operation. Since this analysis focuses on heat generation, the forward voltage V_F at which the heat consumption is highest is estimated from the voltage and current indicated in the data sheet (Fig. 13).

We push forward to achieve a circuit design having a design margin that can accommodate the error of the newly estimated electric model and the error (about 10% in average) of the previously adjusted electric model.

Besides the above, diodes also involve adjustment of other characteristics including capacity and reverse recovery. However, this analysis uses the electric model provided by the manufacturer as is. The electric and thermal models of the diode are shown in Fig. 14.

5.4 FET

The field-effect transistor (FET) is a type of semiconductor components with three terminals: source, gate and drain. FETs control the flow of current between the drain and source by applying a voltage across the gate and source.

FET manufacturers provide SPICE-based electric models of FETs. FETs feature the gate voltage (point Q) at which the current between the drain and source is constant, not depending on the temperature. Fig. 15 shows the V_G-I_D characteristics of an electric model provided by FET manufacturers, in which the characteristics curves at different temperatures do not intersect with each other. In this case, the parameters should be adjusted so that the curves intersect at the point Q as shown in Fig. 16.

The gate-to-source voltage (gate threshold voltage) that is necessary to turn the FET on is dependent on temperature. Since a difference was found between the manufacturer's electric model and the data sheet as shown in Fig.17, the drain current around 1 A, where accuracy is required, has been adjusted (Fig. 18). After the electric model is adjusted, a thermal model should be created (Fig. 19).

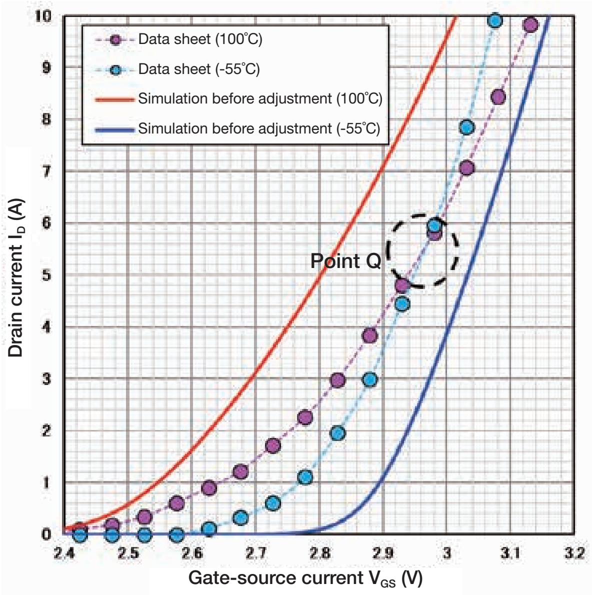


Fig. 15 V_G-I_D characteristics of electric model provided by manufacturer

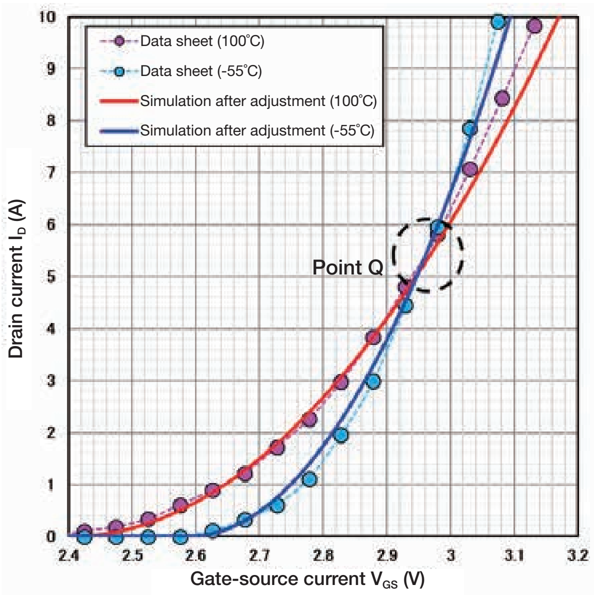


Fig. 16 V_G-I_D characteristics after adjustment

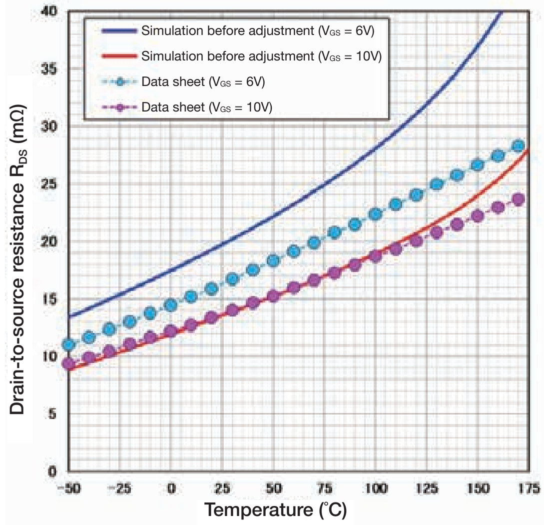


Fig. 17 T_a-R_{DS} characteristics of electric model provided by manufacturer

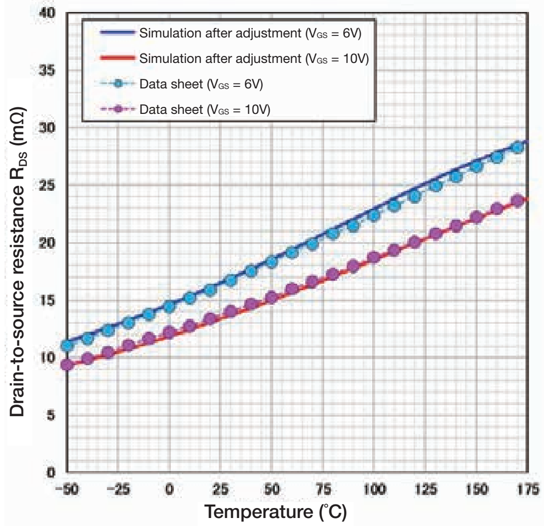


Fig. 18 Adjusted T_a-R_{DS} characteristics

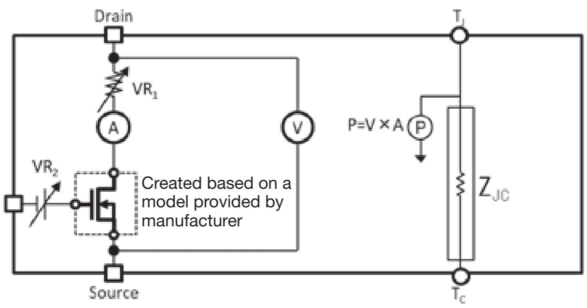


Fig. 19 Electric and thermal models of FET

6 Development Flow

The following lists the flow of development of PCB implementation:

[1] Define the specifications.
[2] Select components and design circuits.
[3] Design a PCB layout.
[4] Design a PCB pattern.
[5] Predict product temperature.
[6] Prototyping and evaluation

If thorough discussion is made in the steps [2] and [3] during the early stage of product development, the number of times of prototyping can be reduced, leading to less rework upon detection of failures during verification tests using actual machines. The following explains the development flow using a specific case of an actuator driving circuit shown in Fig. 20. The FET, diode, and resistance are components that can generate heat.

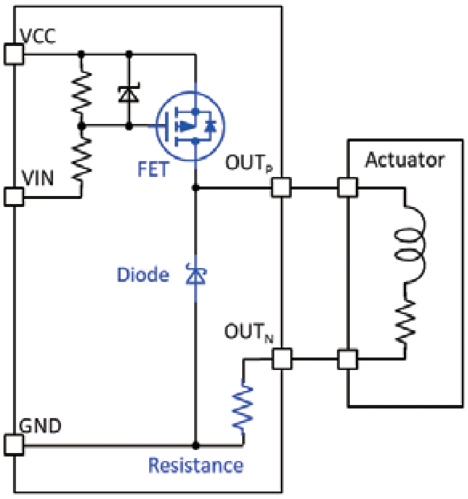


Fig. 20 Actuator driving circuit

6.1 Selecting Components

The key points in selecting components are to satisfy the operating temperature specifications and to ensure the life.

In terms of the operating temperature specifications, components should be selected so that their temperature is within the service temperature range during assumed circuit operation.

The life of components can be estimated from the service environment of the product (a period of time for each temperature range). For example, in-vehicle grade semiconductors are often subjected to a reliability test at 150˚C for 1,000 hours. In order for the semiconductor to satisfy the test conditions, the load current, power consumption and thermal resistance of each electronic component should be estimated and appropriate components should be selected so that the upper temperature limit will not be exceeded.

The power consumption of the overall circuit under the conditions where the selected heat-generating components satisfy the points above should also be calculated, from which the minimum board size can be determined for temporary selection (Fig. 21). Remember that the smaller the board size is, the higher the thermal density is.

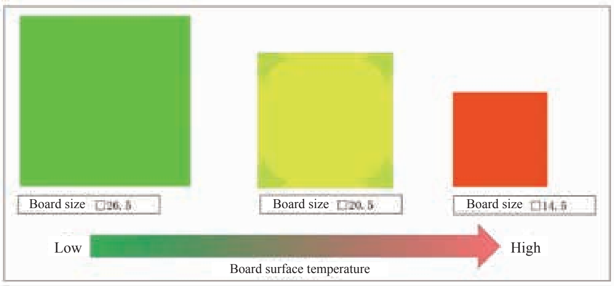


Fig. 21 Relationship between board size and board surface temperature

Boards at higher temperatures need to use high-temperature-resistant components, which are usually expensive. Thus, it is important to consider the balance between cost and size (compactness).

6.2 Designing Circuits

A circuit diagram should be created and the operation be verified through theoretical calculation and using simulation tools. In addition, the source voltage and ambient temperature variations should be determined for improved robustness, and the operation under the worst conditions should be verified with considerations given to variation in components. The worst conditions may be difficult to set up through measurement, but can easily be identified through simulation.

6.3 Analyzing Component Life

The life of the product with the highest heat consumption ("Max." in Table 3) is predicted with a simulation. As an example, the results of a simulation predicting the life of a FET are shown in Fig. 22. It can be determined from the figure that the life is within 1,000 hours at 150˚C, as guaranteed by the manufacturer.

Table 3 Highest heat consumption with manufacturing dispersion

Power consumption (W)		
Min	Typ	Max
0.42	0.54	0.62

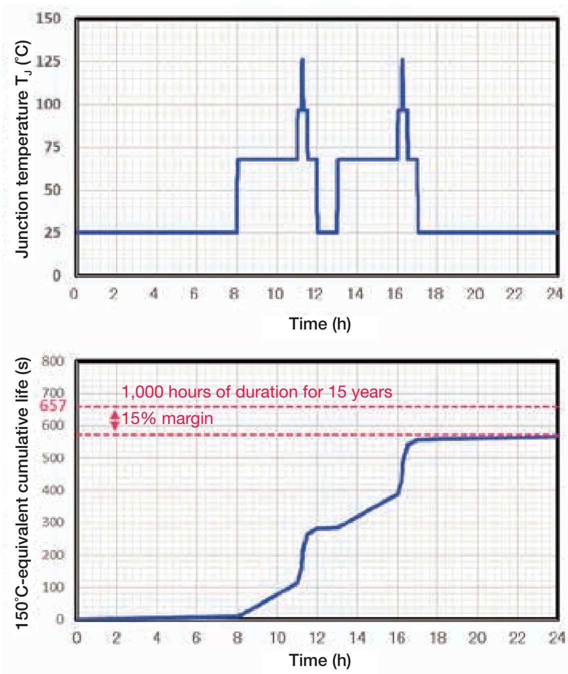


Fig. 22 FET life prediction

6.4 Designing Board Layout

The electric and thermal models using the temporarily selected board size under the worst conditions is analyzed to determine the thermal distribution. If the temperature in a thermally concentrated location is out of the service temperature range, the arrangement and board size should be adjusted so as to achieve the target temperature. Figs. 23 to 25 indicate the results of 1D and 3D simulations. Fig. 23 shows an example that does not meet the requirements because the component temperature exceeds the upper limit due to an excessively small board. Fig. 24 shows an example in which the board size is larger than necessary while the component temperature is very favorable. Fig. 25 shows an example in which the component temperature and board size are both appropriate.

7 Prototype Evaluation

We have decided the board size based on the results of the 1D simulation and prototyped a board (Photo 1).

We measured the temperature of the on-board components and compared it to the simulation results. The component that showed the highest temperature is the diode, and the difference in temperature between the measurements and the 1D simulation is within 3˚C (Fig. 26). For the most part, the temperature distribution obtained with the 3D simulation represents similar trend to that obtained with actual measurements (Fig. 27).

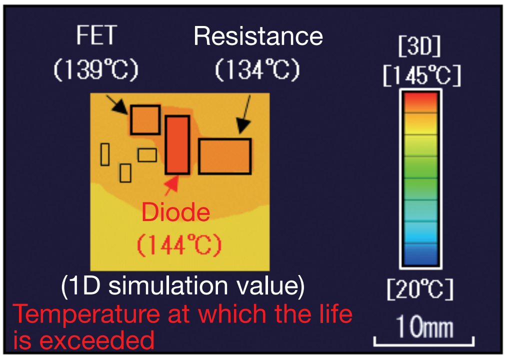


Fig. 23 Excessively small board

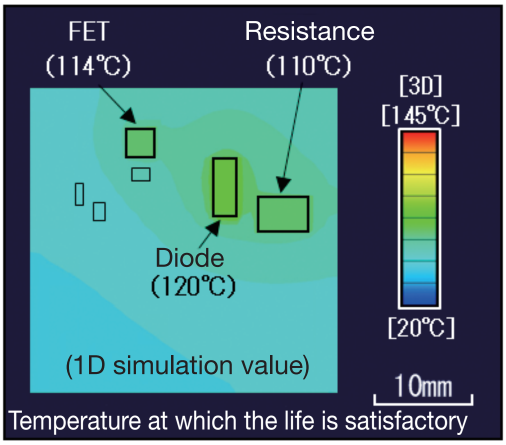


Fig. 24 Excessively large board

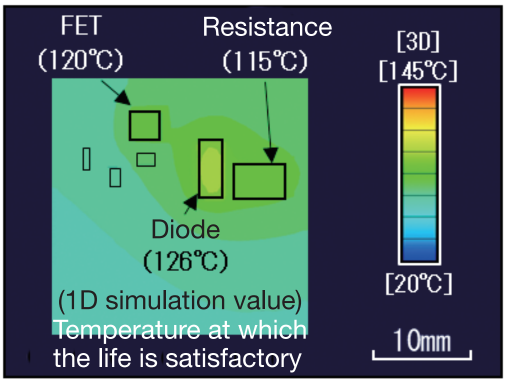


Fig. 25 Board of proper size

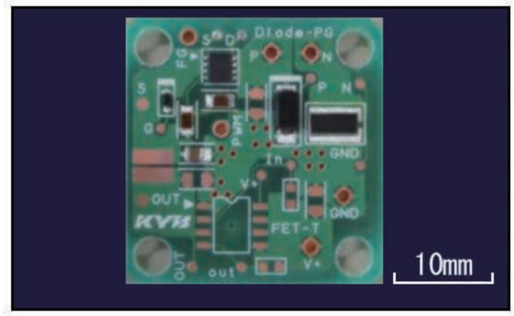


Photo 1 Prototyped board

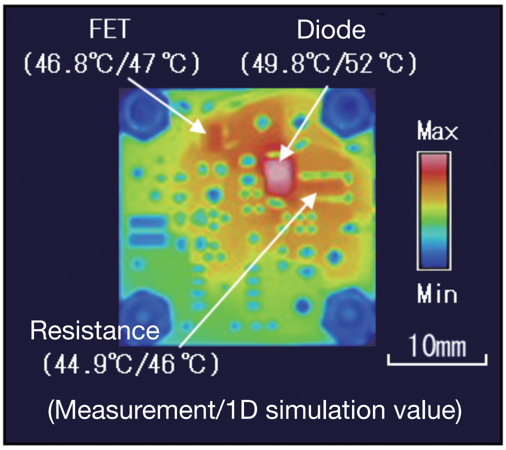


Fig. 26 Comparison between test and 1D simulation

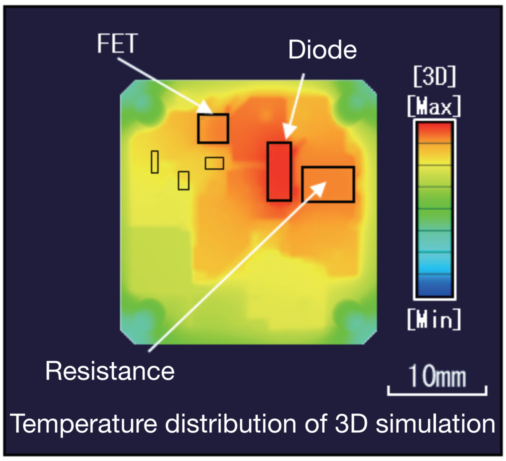


Fig. 27 Results of 3D simulation

Since components at higher temperatures have shorter life, the small difference in temperature of the component with the highest temperature between the measurements and the simulation implies that the results are desirable.

8 Concluding Remarks

We conducted thermal analysis with 1D simulation using electric and thermal models and also carried out actual measurement of the temperature of a prototyped PCB. The results showed that the difference in temperature of heat-generating components between prediction and measurement was 20% or less. We also found that compared to the 3D simulation with thermal fluid analysis, 1D simulation requires a substantially shorter time to obtain calculation results. If it becomes possible to predict the temperature without 3D simulation, the feasibility of a PCB design of a required size can be determined in the conceptual design stage of the initial development phase. This will lead to lower possibility of rework after the 3D profile design has been completed, achieving higher efficiency of total development.

Moving forward, we will accumulate data supported by actual measurements to promote parameter optimization of various models. By improving the accuracy of initial thermal analysis of new products being developed, we are committed to higher efficiency and higher added value for electronics product development.

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