

Understanding Power MOSFETs

Introduction

Power MOSFETs (Metal Oxide Semiconductor, Field Effect Transistors) differ from bipolar transistors in operating principles, specifications, and performance. The performance characteristics of MOSFETs are generally superior to those of bipolar transistors: significantly faster switching time, simpler drive circuitry, the absence of or reduction of the second-breakdown failure mechanism, the ability to be paralleled, and stable gain and response time over a wide temperature range. This note provides a basic explanation of general MOSFET characteristics, and a more thorough discussion of structure, thermal characteristics, gate parameters, operating frequency, output characteristics, and drive requirements.

General Characteristics

A conventional n-p-n bipolar power transistor is a current-driven device whose three terminals (base, emitter, and collector) are connected to the silicon by alloyed metal contacts. Bipolar transistors are described as minority-carrier devices in which injected minority carriers recombine with majority carriers. A drawback of recombination is that it limits the device's operating speed. And because of its current-driven base-emitter input, a bipolar transistor presents a low-impedance load to its driving circuit. In most power circuits, this low-impedance input requires somewhat complex drive circuitry.

By contrast, a power MOSFET is a voltage-driven device whose gate terminal, Figure 1(a), is electrically isolated from its silicon body by a thin layer of silicon dioxide (SiO_2). As a majority-carrier semiconductor, the MOSFET operates at much higher speed than its bipolar counterpart because there is no charge-storage mechanism. A positive voltage applied to the gate of an n-type MOSFET creates an electric field in the channel region beneath the gate; that is, the electric charge on the gate causes the p-region beneath the gate to convert to an n-type region, as shown in Figure 1(b). This conversion, called the surface-inversion phenomenon, allows current to flow between the drain and source through an n-type material. In effect, the MOSFET ceases to be an n-p-n device when in this state. The region between the drain and source can be represented as a resistor, although it does not behave linearly, as a conventional resistor would. Because of this surface-inversion phenomenon, then, the operation of a MOSFET is entirely different from that of a bipolar transistor, which always retain its n-p-n characteristic.

By virtue of its electrically-isolated gate, a MOSFET is described as a high-input impedance, voltage-controlled device, whereas a bipolar transistor is a low-input-impedance, current-controlled device. As a majority-carrier semiconductor, a MOSFET stores no charge, and so can switch faster than a bipolar device. Majority-carrier semiconductors also tend to slow down as temperature increases. This effect, brought about by another phenomenon called carrier mobility (where mobility is a term that defines the average velocity of a carrier in terms of the electrical field imposed on it) makes a MOSFET more resistive at elevated temperatures, and much more immune to the thermal-runaway problem experienced by bipolar devices.

A useful by-product of the MOSFET process is the internal parasitic diode formed between source and drain, Figure 1, section C. (There is no equivalent for this diode in a bipolar transistor other than in a bipolar Darlington transistor.) Its characteristics make it useful as a clamp diode in inductive-load switching.

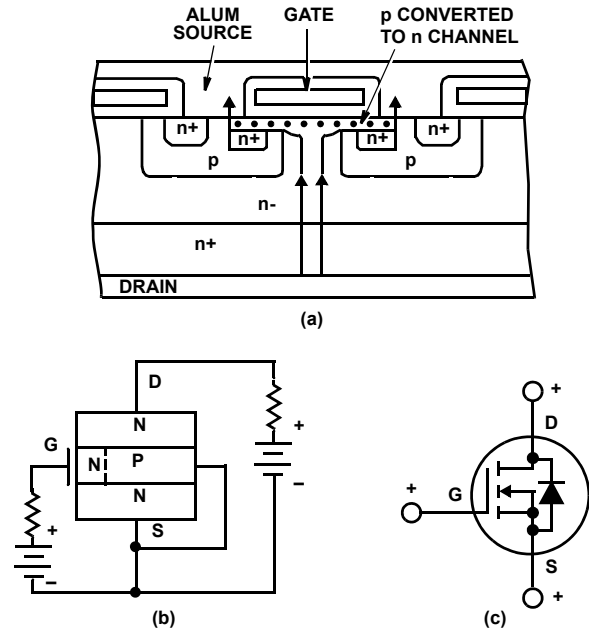


FIGURE 1. THE MOSFET, A VOLTAGE-CONTROLLED DEVICE WITH AN ELECTRICALLY ISOLATED GATE, USES MAJORITY CARRIERS TO MOVE CURRENT FROM SOURCE TO DRAIN (A). THE KEY TO MOSFET OPERATION IS THE CREATION OF THE INVERSION CHANNEL BENEATH THE GATE WHEN AN ELECTRIC CHARGE IS APPLIED TO THE GATE (B). BECAUSE OF THE MOSFETS CONSTRUCTION, AN INTEGRAL DIODE IS FORMED ON THE DEVICE (C), AND THE DESIGNER CAN USE THIS DIODE FOR A NUMBER OF CIRCUIT FUNCTIONS

STRUCTURE

Intersil Power MOSFETs are manufactured using a vertical double-diffused process, called VDMOS or simply DMOS. A DMOS MOSFET is a single silicon chip structured with a large number of closely packed, hexagonal cells. The number of cell varies according to the dimensions of the chip. For example, a 120-mil² chip contains about 5,000 cells; a 240-mil² chip has more than 25,000 cells.

One of the aims of multiple-cells construction is to minimize the MOSFET parameter $r_{DS(ON)}$, or resistance from drain to source, when the device is in the on-state. When $r_{DS(ON)}$ is minimized, the device provides superior power-switching performance because the voltage drop from drain to source is also minimized for a given value of drain-to-source current.

Since the path between drain and source is essentially resistive, because of the surface-inversion phenomenon, each cell in the device can be assumed to contribute an amount, R_N , to the total resistance. An individual cell has a fairly low

resistance, but to minimize $r_{DS(ON)}$, it is necessary to put a large number of cells in parallel on a chip. In general, therefore, the greater the number of paralleled cells on a chip, the lower its $r_{DS(ON)}$ value:

$$r_{DS(ON)} = R_N/N, \text{ where } N \text{ is the number of cells.}$$

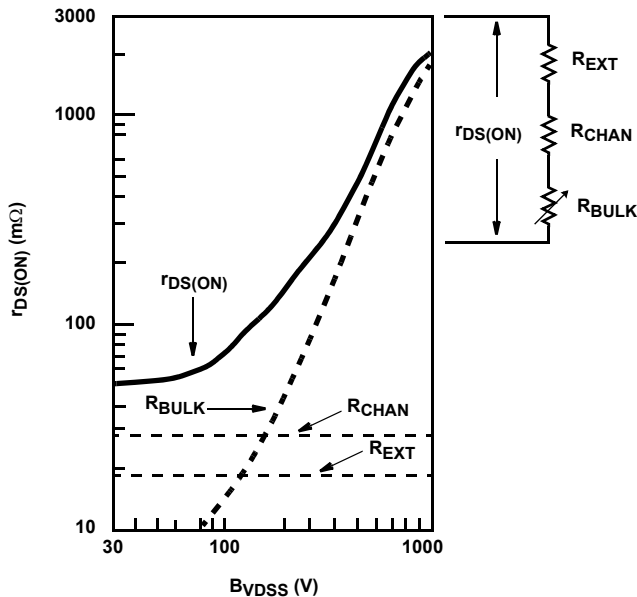


FIGURE 2. THE DRAIN-TO-SOURCE RESISTANCE, $r_{DS(ON)}$, OF A MOSFET IS NOT ONE BUT THREE SEPARATE RESISTANCE COMPONENTS

TABLE 1. PERCENTAGE RESISTANCE COMPONENTS FOR A TYPICAL CHIP

BV_{DSS}	40V	150V	500V
$R_{CHANNEL}$	50%	23%	2.4%
R_{BULK}	35%	70%	97%
$R_{EXTERNAL}$	15%	7%	<1%

In reality, $r_{DS(ON)}$ is composed of three separate resistances. Figure 2 shows a curve of the three resistive components for a single cell and their contributions to the overall value of $r_{DS(ON)}$. The value of $r_{DS(ON)}$ at any point of the curve is found by adding the values of the three components at that point:

$$r_{DS(ON)} = R_{BULK} + R_{CHAN} + R_{EXT}$$

where R_{CHAN} represents the resistance of the channel beneath the gate, and R_{EXT} includes all resistances resulting from the substrate, solder connections, leads, and the package. R_{BULK} represents the resistance resulting from the narrow neck of n material between the two layers, as shown in Figure 1(a), plus the resistance of the current path below the neck and through the body to the substrate region of the device.

Note in Figure 2 that R_{CHAN} and R_{EXT} are completely independent of voltage, while R_{BULK} is highly dependent on applied voltage. Note also that below about 150 volts, $r_{DS(ON)}$ is dominated by the sum of R_{CHAN} and R_{EXT} . Above 150 volts, $r_{DS(ON)}$ is increasingly dominated by R_{BULK} . Table 1 gives a percentage breakdown of the contribution of each resistance for three values of voltage.

Two conclusions, inherent consequences of the laws of semiconductor physics, and valid for any DMOS device, can be drawn from the preceding discussion: First, $r_{DS(ON)}$ obviously increases with increasing breakdown-voltage capability of a MOSFET. Second, minimum $r_{DS(ON)}$ performance must be sacrificed if the MOSFET must withstand ever-higher breakdown voltages.

The significance of R_{BULK} in devices with a high voltage capability is due to the fact that thick, lightly doped epi layers are required for the drain region in order to avoid producing high electric fields (and premature breakdown) within the device. And as the epi layers are made thicker and less resistive to support high voltages, the bulk component of resistance rapidly increases (see Figure 2) and begins to dominate the channel and external resistance. The $r_{DS(ON)}$ therefore, increases with increasing breakdown voltage capability, and low $r_{DS(ON)}$ must be sacrificed if the MOSFET is to withstand even higher breakdown voltages.

There is a way around these obstacles. The $r_{DS(ON)}$ in Figure 2 holds only for a given cell and chip size. Using a larger chip results in a lower value for $r_{DS(ON)}$ because a large chip has more cells (see Figure 3), shifting the vertical axis for each of the constituent parts.

The penalty for using a larger chip, however, is an increase in cost, since chip size is a major cost factor. And because chip area increases exponentially, not linearly, with voltage, the additional cost can be substantial. For example, to obtain a given $r_{DS(ON)}$ at a breakdown voltage twice as great as the original, the new chip requires an area four or five times larger than the original. Although the cost does not rise exponentially, it is substantially more than the original cost.

EFFECTS OF TEMPERATURE

The high operating temperatures of bipolar transistors are frequent cause of failure. The high temperatures are caused by hot-spotting, the tendency of current in a bipolar device to concentrate in areas around the emitter. Unchecked, this hot-spotting results in the mechanism of thermal runaway, and eventual destruction of the device. MOSFETs do not suffer this disadvantage because their current flow is in the form of majority carriers. The mobility of majority carriers (where, again, mobility is a term that defines the average velocity of a carrier in terms of the electrical field imposed on it) is temperature dependent in silicon: mobility decreases with increasing temperature. This inverse relationship dictates that the carriers slowdown as the chip gets hotter. In effect, the resistance of the silicon path is increased, which prevents the concentrations of current that lead to hot spots. In fact, if hot spots do attempt to form in a MOSFET, the local resistance increases and defocuses or spreads out the current, rerouting it to cooler portions of the chip.

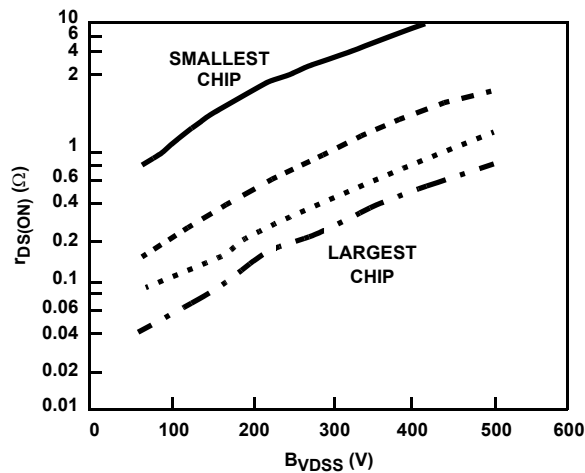


FIGURE 3. AS CHIP SIZE INCREASES, $r_{DS(ON)}$ DECREASES

Because of the character of its silicon structure, a MOSFET has a positive temperature coefficient of resistance, as shown by the curves of Figure 4.

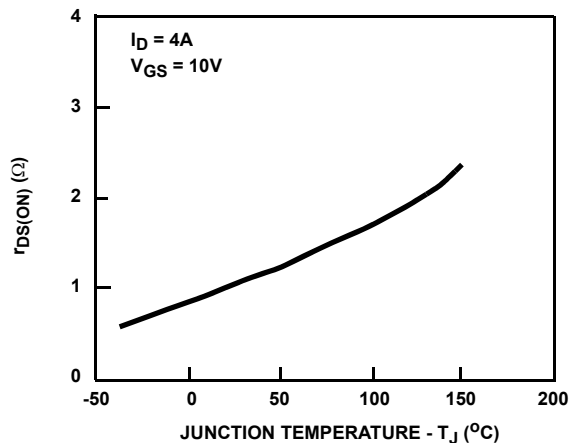


FIGURE 4. MOSFETS HAVE A POSITIVE TEMPERATURE COEFFICIENT OF RESISTANCE, WHICH GREATLY REDUCES THE POSSIBILITY OF THERMAL RUNAWAY AS TEMPERATURE INCREASES

The positive temperature coefficient of resistance means that a MOSFET is inherently more stable with temperature fluctuation, and provides its own protection against thermal runaway and second breakdown. Another benefit of this characteristic is that MOSFETs can be operated in parallel without fear that one device will rob current from the others. If any device begins to overheat, its resistance will increase, and its current will be directed away to cooler chips.

GATE PARAMETERS

To permit the flow of drain-to-source current in an n-type MOSFET, a positive voltage must be applied between the gate and source terminals. Since, as described above, the gate is electrically isolated from the body of the device, theoretically no current can flow from the driving source into the gate. In reality, however, a very small current, in the range of tens of nanoamperes, does flow, and is identified on data sheets as a leakage current, I_{GSS} .

Because the gate current is so small, the input impedance of a MOSFET is extremely high (in the megohm range) and, in fact, is largely capacitive rather than resistive (because of the isolation of the gate terminal).

Figure 5 illustrates the basic input circuit of a MOSFET. The elements are equivalent, rather than physical, resistance, R , and capacitance, C . The capacitance, called C_{ISS} on MOSFET data sheets, is a combination of the device's internal gate-to-source and gate-to-drain capacitance. The resistance, R , represents the resistance of the material in the gate circuit. Together, the equivalent R and C of the input circuit will determine the upper frequency limit of MOSFET operation.

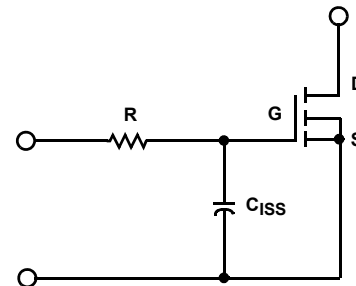


FIGURE 5. A MOSFETS SWITCHING SPEED IS DETERMINED BY ITS INPUT RESISTANCE R AND ITS INPUT CAPACITANCE C_{ISS}

OPERATING FREQUENCY

Most DMOS processes use a polysilicon gate structure rather than the metal-gate type. If the resistance of the gate structure (R in Figure 5) is high, the switching time of the DMOS device is increased, thereby reducing its upper operating frequency. Compared to a metal gate, a polysilicon gate has a higher gate resistance. This property accounts for the frequent use of metal-gate MOSFETs in high-frequency (greater than 20MHz) applications, and polysilicon-gate MOSFETs in higher-power but lower-frequency systems.

Since the frequency response of a MOSFET is controlled by the effective R and C of its gate terminal, a rough estimate can be made of the upper operating frequency from datasheet parameters. The resistive portion depends on the sheet resistance of the polysilicon-gate overlay structure, a value of approximately 20 ohms. But whereas the total R value is not found on datasheets, the C value (C_{ISS}) is; it is recorded as both a maximum value and in graphical form as a function of drain-to-source voltage. The value of C_{ISS} is closely related to chip size; the larger the chip, the greater the value. Since the RC combination of the input circuit must be charged and discharged by the driving circuit, and since the capacitance dominates, larger chips have slower switching times than smaller chips, and are more useful in lower-frequency circuits. In general, the upper frequency limit of most power MOSFETs spans a fairly broad range, from 1MHz to 10MHz.

OUTPUT CHARACTERISTICS

Probably the most used MOSFET graphical data is the output characteristics or a plot of drain-to-source current (I_{DS}) as a function of drain-to-source voltage (V_{DS}). A typical characteristic, shown in Figure 6, gives the drain current that flows at various V_{DS} values as a function of the gate-to-source voltage (V_{GS}). The curve is divided into two regions: a linear region in which V_{DS} is small and drain current increases linearly with drain voltage, and a saturated region in which increasing drain voltage has no effect on drain current (the device acts as a constant-current source). The current level at which the linear portion of the curve joins with the saturated portion is called the pinch-off region.

DRIVE REQUIREMENTS

When considering the V_{GS} level required to operate a MOSFET, note from Figure 6, that the device is not turned on (no drain current flows) unless V_{GS} is greater than a certain level (called the threshold voltage). In other words, the threshold voltage must be exceeded before an appreciable increase in drain current can be expected. Generally V_{GS} for many types of DMOS devices is at least 2V. This is an important consideration when selecting devices or designing circuits to drive a MOSFET gate: the gate-drive circuit must provide at least the threshold-voltage level, but preferably, a much higher one.

As Figure 6 shows, a MOSFET must be driven by a fairly high voltage, on the order of 10V, to ensure maximum saturated drain-current flow. However, integrated circuits, such as TTL types, cannot deliver the necessary voltage levels unless they are modified with external pull-up resistors. Even with a pull-up to 5V, a TTL driver cannot fully saturate most MOSFETs. Thus, TTL drivers are most suitable when the current to be switched is far less than the rated current of the MOSFET. CMOS ICs can run from supplies of 10V, and these devices are capable of driving a MOSFET into full saturation. On the other hand, a CMOS driver will not switch the MOSFET gate circuit as fast as a TTL driver. The best results, whether TTL or CMOS ICs provide the drive, are achieved when special buffering chips are inserted between the IC output and gate input to match the needs of the MOSFET gate.

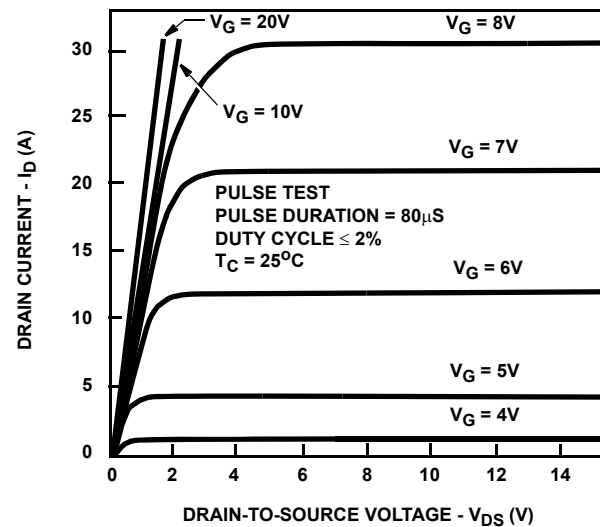


FIGURE 6. MOSFETS REQUIRE A HIGH INPUT VOLTAGE (AT LEAST 10V) IN ORDER TO DELIVER THEIR FULL RATED DRAIN CURRENT

Notice

1. Descriptions of circuits, software and other related information in this document are provided only to illustrate the operation of semiconductor products and application examples. You are fully responsible for the incorporation or any other use of the circuits, software, and information in the design of your product or system. Renesas Electronics disclaims any and all liability for any losses and damages incurred by you or third parties arising from the use of these circuits, software, or information.
2. Renesas Electronics hereby expressly disclaims any warranties against and liability for infringement or any other claims involving patents, copyrights, or other intellectual property rights of third parties, by or arising from the use of Renesas Electronics products or technical information described in this document, including but not limited to, the product data, drawings, charts, programs, algorithms, and application examples.
3. No license, express, implied or otherwise, is granted hereby under any patents, copyrights or other intellectual property rights of Renesas Electronics or others.
4. You shall not alter, modify, copy, or reverse engineer any Renesas Electronics product, whether in whole or in part. Renesas Electronics disclaims any and all liability for any losses or damages incurred by you or third parties arising from such alteration, modification, copying or reverse engineering.
5. Renesas Electronics products are classified according to the following two quality grades: "Standard" and "High Quality". The intended applications for each Renesas Electronics product depends on the product's quality grade, as indicated below.
"Standard": Computers; office equipment; communications equipment; test and measurement equipment; audio and visual equipment; home electronic appliances; machine tools; personal electronic equipment; industrial robots; etc.
"High Quality": Transportation equipment (automobiles, trains, ships, etc.); traffic control (traffic lights); large-scale communication equipment; key financial terminal systems; safety control equipment; etc.
Unless expressly designated as a high reliability product or a product for harsh environments in a Renesas Electronics data sheet or other Renesas Electronics document, Renesas Electronics products are not intended or authorized for use in products or systems that may pose a direct threat to human life or bodily injury (artificial life support devices or systems; surgical implantations; etc.), or may cause serious property damage (space system; undersea repeaters; nuclear power control systems; aircraft control systems; key plant systems; military equipment; etc.). Renesas Electronics disclaims any and all liability for any damages or losses incurred by you or any third parties arising from the use of any Renesas Electronics product that is inconsistent with any Renesas Electronics data sheet, user's manual or other Renesas Electronics document.
6. When using Renesas Electronics products, refer to the latest product information (data sheets, user's manuals, application notes, "General Notes for Handling and Using Semiconductor Devices" in the reliability handbook, etc.), and ensure that usage conditions are within the ranges specified by Renesas Electronics with respect to maximum ratings, operating power supply voltage range, heat dissipation characteristics, installation, etc. Renesas Electronics disclaims any and all liability for any malfunctions, failure or accident arising out of the use of Renesas Electronics products outside of such specified ranges.
7. Although Renesas Electronics endeavors to improve the quality and reliability of Renesas Electronics products, semiconductor products have specific characteristics, such as the occurrence of failure at a certain rate and malfunctions under certain use conditions. Unless designated as a high reliability product or a product for harsh environments in a Renesas Electronics data sheet or other Renesas Electronics document, Renesas Electronics products are not subject to radiation resistance design. You are responsible for implementing safety measures to guard against the possibility of bodily injury, injury or damage caused by fire, and/or danger to the public in the event of a failure or malfunction of Renesas Electronics products, such as safety design for hardware and software, including but not limited to redundancy, fire control and malfunction prevention, appropriate treatment for aging degradation or any other appropriate measures. Because the evaluation of microcomputer software alone is very difficult and impractical, you are responsible for evaluating the safety of the final products or systems manufactured by you.
8. Please contact a Renesas Electronics sales office for details as to environmental matters such as the environmental compatibility of each Renesas Electronics product. You are responsible for carefully and sufficiently investigating applicable laws and regulations that regulate the inclusion or use of controlled substances, including without limitation, the EU RoHS Directive, and using Renesas Electronics products in compliance with all these applicable laws and regulations. Renesas Electronics disclaims any and all liability for damages or losses occurring as a result of your noncompliance with applicable laws and regulations.
9. Renesas Electronics products and technologies shall not be used for or incorporated into any products or systems whose manufacture, use, or sale is prohibited under any applicable domestic or foreign laws or regulations. You shall comply with any applicable export control laws and regulations promulgated and administered by the governments of any countries asserting jurisdiction over the parties or transactions.
10. It is the responsibility of the buyer or distributor of Renesas Electronics products, or any other party who distributes, disposes of, or otherwise sells or transfers the product to a third party, to notify such third party in advance of the contents and conditions set forth in this document.
11. This document shall not be reprinted, reproduced or duplicated in any form, in whole or in part, without prior written consent of Renesas Electronics.
12. Please contact a Renesas Electronics sales office if you have any questions regarding the information contained in this document or Renesas Electronics products.
(Note 1) "Renesas Electronics" as used in this document means Renesas Electronics Corporation and also includes its directly or indirectly controlled subsidiaries.
(Note 2) "Renesas Electronics product(s)" means any product developed or manufactured by or for Renesas Electronics.

(Rev.4.0-1 November 2017)



SALES OFFICES

Renesas Electronics Corporation

<http://www.renesas.com>

Refer to "<http://www.renesas.com/>" for the latest and detailed information.

Renesas Electronics America Inc.
1001 Murphy Ranch Road, Milpitas, CA 95035, U.S.A.
Tel: +1-408-432-8888, Fax: +1-408-434-5351

Renesas Electronics Canada Limited
9251 Yonge Street, Suite 8309 Richmond Hill, Ontario Canada L4C 9T3
Tel: +1-905-237-2004

Renesas Electronics Europe Limited
Dukes Meadow, Millboard Road, Bourne End, Buckinghamshire, SL8 5FH, U.K
Tel: +44-1628-651-700, Fax: +44-1628-651-804

Renesas Electronics Europe GmbH
Arcadiastrasse 10, 40472 Düsseldorf, Germany
Tel: +49-211-6503-0, Fax: +49-211-6503-1327

Renesas Electronics (China) Co., Ltd.
Room 1709 Quantum Plaza, No.27 ZhichunLu, Haidian District, Beijing, 100191 P. R. China
Tel: +86-10-8235-1155, Fax: +86-10-8235-7679

Renesas Electronics (Shanghai) Co., Ltd.
Unit 301, Tower A, Central Towers, 555 Langao Road, Putuo District, Shanghai, 200333 P. R. China
Tel: +86-21-2226-0888, Fax: +86-21-2226-0999

Renesas Electronics Hong Kong Limited
Unit 1601-1611, 16/F., Tower 2, Grand Century Place, 193 Prince Edward Road West, Mongkok, Kowloon, Hong Kong
Tel: +852-2265-6688, Fax: +852-2886-9022

Renesas Electronics Taiwan Co., Ltd.
13F, No. 363, Fu Shing North Road, Taipei 10543, Taiwan
Tel: +886-2-8175-9600, Fax: +886-2-8175-9670

Renesas Electronics Singapore Pte. Ltd.
80 Bendemeer Road, Unit #06-02 Hyflux Innovation Centre, Singapore 339949
Tel: +65-6213-0200, Fax: +65-6213-0300

Renesas Electronics Malaysia Sdn.Bhd.
Unit 1207, Block B, Menara Amcorp, Amcorp Trade Centre, No. 18, Jln Persiaran Barat, 46050 Petaling Jaya, Selangor Darul Ehsan, Malaysia
Tel: +60-3-7955-9390, Fax: +60-3-7955-9510

Renesas Electronics India Pvt. Ltd.
No.777C, 100 Feet Road, HAL 2nd Stage, Indiranagar, Bangalore 560 038, India
Tel: +91-80-67208700, Fax: +91-80-67208777

Renesas Electronics Korea Co., Ltd.
17F, KAMCO Yangjae Tower, 262, Gangnam-daero, Gangnam-gu, Seoul, 06265 Korea
Tel: +82-2-558-3737, Fax: +82-2-558-5338