MOSFET Gate Drive Circuit

Description

This document describes gate drive circuits for power MOSFETs.

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1. Driving a MOSFET

1.1. Gate drive vs. base drive

Whereas the conventional bipolar transistor is a current-driven device, the MOSFET is a voltage-driven device.

Figure 1.1 illustrates a bipolar transistor. A current must be applied between the base and emitter terminals to produce a flow of current in the collector. Figure 1.2 shows a MOSFET, which produces a flow of current in the drain when a voltage is applied between the gate and source terminals.

The gate of a MOSFET is composed of a silicon oxide layer. Since the gate is insulated from the source, an application of a DC voltage to the gate terminal does not theoretically cause a current to flow in the gate, except in transient periods during which the gate is charged and discharged. In practice, the gate has a tiny current on the order of a few nanoamperes. When there is no voltage between the gate and source terminals, no current flows in the drain except leakage current, because of a very high drain-source impedance.

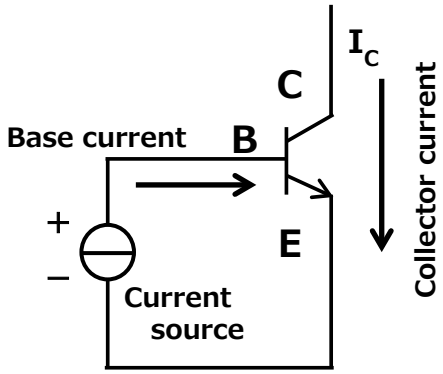


Figure 1.1 Driving a bipolar transistor

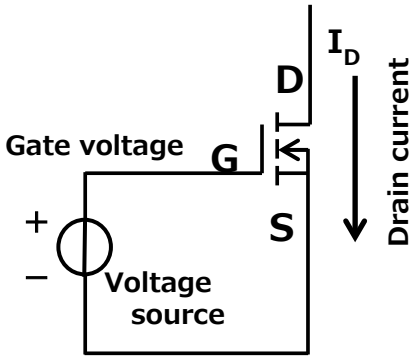


Figure 1.2 Driving a MOSFET

1.2. MOSFET characteristics

MOSFETs have the following characteristics:

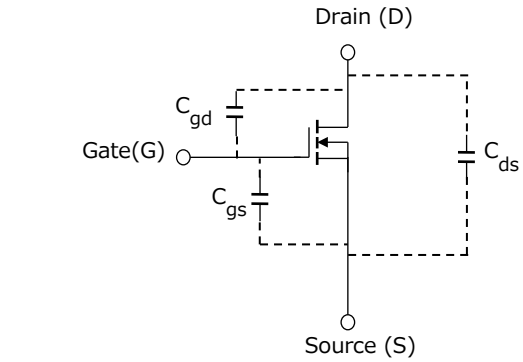
- Since the MOSFET is a voltage-driven device, no DC current flows into the gate.
- In order to turn on a MOSFET, a voltage higher than the rated gate threshold voltage V_{th} must be applied to the gate.
- While in a steady on or off state, the MOSFET gate drive basically consumes no power.
- The gate-source capacitance of a MOSFET seen by the driver output varies with its internal state.

MOSFETs are often used as switching devices at frequencies ranging from several kHz to more than several hundreds of kHz. The low power consumption needed for gate drive is an advantage of a MOSFET as a switching device. MOSFETs designed for low-voltage drive are also available.

1.2.1. Gate charge

The gate of a MOSFET can be considered to be a capacitance. Figure 1.3 shows different capacitances in a MOSFET. The gate voltage of a MOSFET does not increase unless its gate input capacitance is charged, and the MOSFET does not turn on until its gate voltage reaches the gate threshold voltage V_{th}. The gate threshold voltage V_{th} of a MOSFET is defined as the minimum gate bias required for creating a conduction channel between its source and drain regions.

In considering a drive circuit and a drive current, the gate charge Q_g of a MOSFET is more important than its capacitances. Figure 1.4 illustrates the definitions of parameters regarding the gate charge necessary to raise the gate voltage.



Input capacitance $C_{iss} = C_{gd} + C_{gs}$

Output capacitance $C_{oss} = C_{ds} + C_{gd}$

Reverse Transfer capacitance $C_{rss} = C_{gd}$

Figure 1.3 Capacitances in a MOSFET

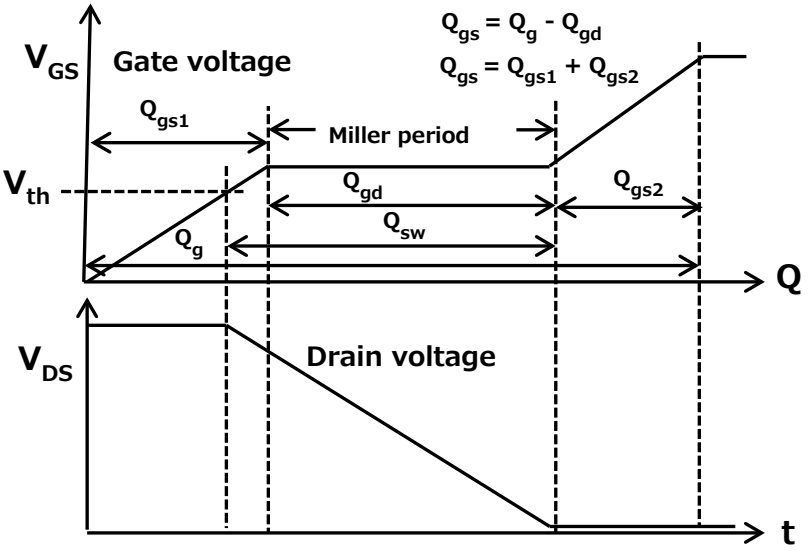


Figure 1.4 Gate charge (resistive load)

1.2.2. Calculating MOSFET gate charge

During the turn-on of a MOSFET, a current flows to its gate, charging the gate-source and gate-drain capacitances. Figure 1.5 shows a test circuit for gate charge. Figure 1.6 shows the gate-source voltage curve over time obtained when a constant current is applied to the gate terminal. Since the gate current is constant, the time axis can be expressed in terms of gate charge Q_g by multiplying time by constant gate current I_G. (The gate charge is calculated as $Q_g = I_G \times t$.)

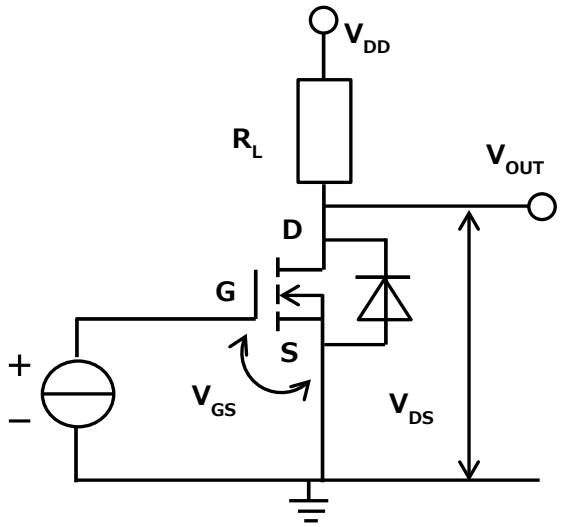


Figure 1.5 Gate charge test circuit

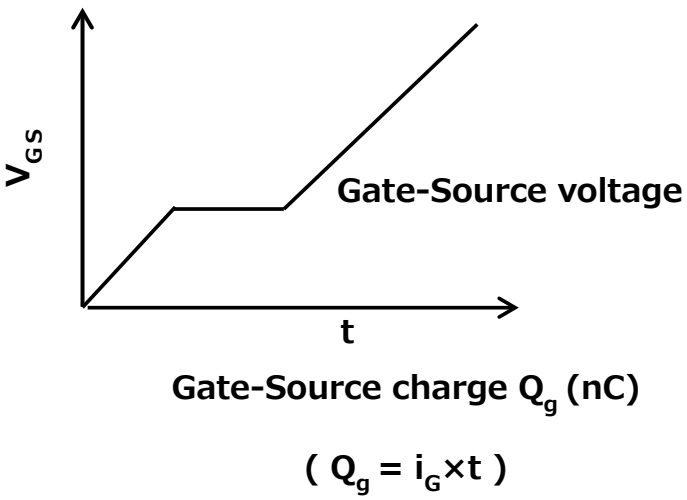


Figure 1.6 Gate charge waveform

1.2.3. Gate charging mechanism

The gate of a MOSFET starts accumulating electric charge when a voltage is applied to it. Figure 1.7 shows a gate charge circuit and a gate charge waveform. When a MOSFET is connected to an inductive load, it affects the reverse recovery current of the diode in parallel to the MOSFET as well as the MOSFET gate voltage. This explanation is omitted here.

① During the period t_0 to t_1, the gate drive circuit charges the gate-source capacitance C_{gs} and the gate-drain capacitance C_{gd} via the gate series resistor R until the gate voltage reaches its threshold V_{th}. Since C_{gs} and C_{gd} are charged in parallel, the following equation is satisfied. The gate voltage V_{GS} is calculated as:

$$v_{GS}(t)= V_G(1-\exp(-t/(R(C_{gs}+C_{gd}))) \quad (1)$$

Hence, substituting V_{th} for $v_{GS}(t_1)$, gate delay time t_1 is obtained as:

$$t_1=R(C_{gs}+C_{gd})\ln(V_G/(V_G-V_{th}))$$

This indicates that the delay time t_1 is proportional to $R(C_{gs}+C_{gd})$.

② During the period t_1 to t_2, V_{GS} exceeds V_{th}, causing a current to flow in the drain, which eventually becomes the main current. C_{gs} and C_g continue to be charged in this period. As the gate voltage increases, the drain current increases. At t_2, the gate voltage reaches the Miller voltage, $V_{GS(pl)}$. t_2 can be calculated by substituting $V_{GS(pl)}$ for $V_{GS}(t_2)$ in Equation (1). As in the period t_0 to t_1, the delay time t_2 is proportional to $R(C_{gs}+C_{gd})$.

$$t_2=R(C_{gs}+C_{gd})\ln(V_G/(V_G-V_{GS(pl)}))$$

$$t_2-t_1=R(C_{gs}+C_{gd})\ln((V_G-V_{th})/(V_G-V_{GS(pl)}))$$

Since the drain current is flowing during this period, a MOSFET suffers a power loss.

③ During the period t_2 to t_3, V_{GS} remains constant at the $V_{GS(pl)}$ voltage (due to the Miller effect). The gate voltage remains constant. As the entire main gate current keeps flowing through the MOSFET, the drain voltage reaches its turn-on voltage, $(R_{DS(on)}\times I_D)$ at t_3. Since the gate voltage remains constant during this period, the drive current flows to C_{gd}, not to C_{gs}. The charge accumulated in C_{gd} (Q_{gd}) during this period equals the product of a current flowing to the gate circuit and the voltage fall time (t_3–t_2):

$$Q_{gd}=(V_G-V_{GS(pl)})/R\cdot(t_3-t_2)$$

Hence, $t_3-t_2=Q_{gd}R_G/(V_G-V_{GS(pl)})$

Since the drain voltage keeps decreasing during this period while the drain current remains constant, the MOSFET suffers a power loss.

④ During the period t_3 to t_4, the gate is charged to the oversaturated state. Both C_{gs} and C_{gd} are charged until the gate voltage (V_{GS}) reaches the gate supply voltage. Since the turn-on transient has already disappeared, the MOSFET suffers no switching loss during this period.

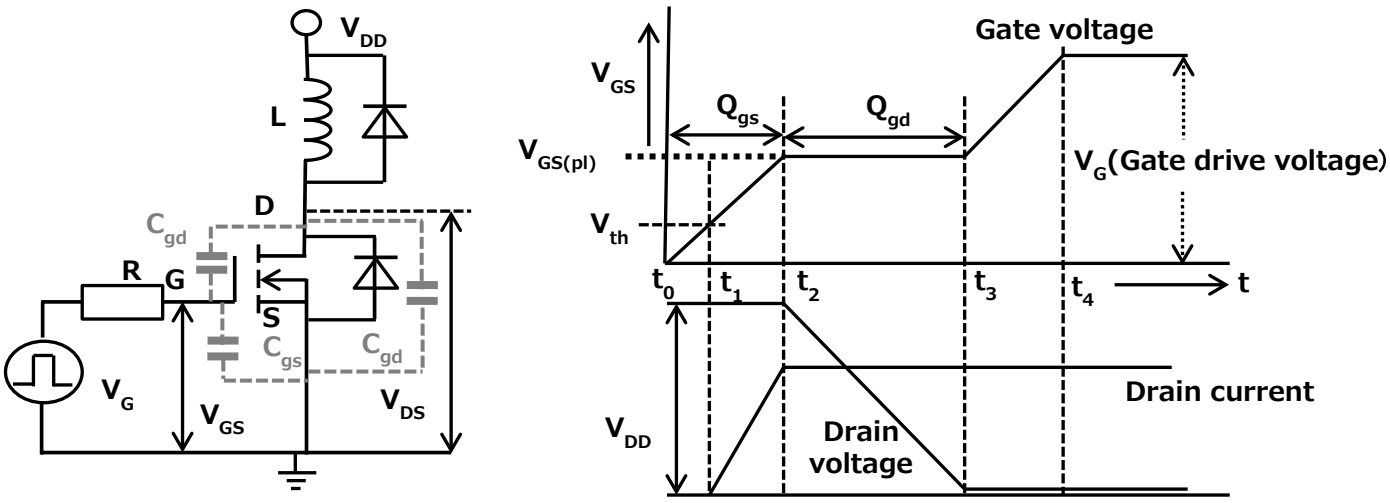
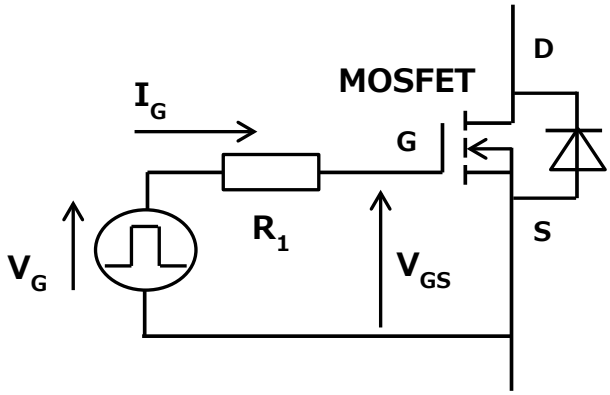


Figure 1.7 Gate charge circuit and waveform (inductive load)

1.3. Gate drive power

The power consumed by the MOSFET gate drive circuit increases in proportion to its frequency. This section describes the power consumption by the gate drive circuit shown in Figure 1.8.



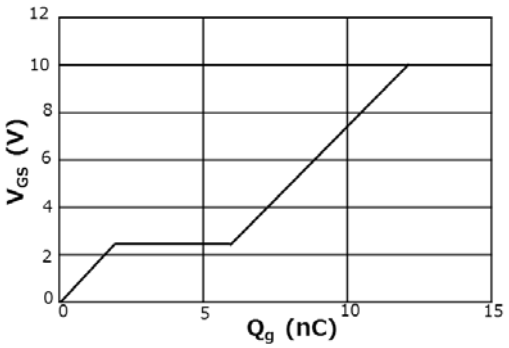


Figure 1.8 MOSFET drive circuit **Figure 1.9 Gate charge characteristics**

In Figure 1.8, a gate pulse voltage V_G is applied between the gate and source terminals of a MOSFET via a gate resistor R_1. Suppose that V_{GS} rises from 0 V to V_G (10 V in Figure 1.9). V_G is sufficiently high to turn on the MOSFET. The MOSFET is initially off and turns on as V_{GS} changes from 0 V to V_G. The gate current flowing during this transient switching period is calculated as:

$$i_G=(V_G-v_{GS})/R_G$$

Hence, the gate-source voltage is calculated as $v_{GS}=V_G-R_G\times i_G$.

The gate charge Q_g can be calculated by integrating the gate current i_G over time.

$$Q_g=\int i_G \, dt$$

The energy E supplied from the gate drive source during the turn-on period is:

$$E=\int v_G \times i_G dt$$

where, v_G is the drive supply voltage. Since the integral of V_G and I_G over time is Q_{gp},

$E=V_G \times Q_{gp}$

Q_g and i_G have the following relationship: $i_G=dQ_g/dt$. Therefore, the energy accumulated in the gate of a MOSFET during its turn-on period E_G is calculated as:

$$E_G = \int v_{Gs} \times i_G dt = \int (v_G \times \frac{dQ_g}{dt}) dt = \int v_{GS} dQ_g$$

The gate charge is the integral of v_{GS} over Q_g from 0 to Q_{gp}, which is shown in Figure 1.10.

The energy supplied from the drive power supply minus the energy accumulated in the gate is consumed by the gate resistor.

During the turn-off period, the energy accumulated in the gate is consumed by the gate resistor.

The energy E consumed per switching event is equal to the amount of energy supplied by the drive circuit. The average power consumption of the gate drive circuit P_G can be calculated by multiplying E by the switching frequency f_{sw}:

$$\mathbf{P_G = E \times f_{sw} = V_G \times Q_{gp} \times f_{sw}}$$

The average power consumption of the gate drive circuit P_G can also be expressed as $\mathbf{P_G = E \times f_{sw} = C_{iss} \times (V_G)^2 \times f_{sw}}$ in terms of the input capacitance. However, the P_G value calculated this way greatly differs from the actual power loss. This is because C_{iss} includes the gate-drain capacitance C_{gd} having the Miller capacitance and is therefore a function of V_{DS} and because the gate-source capacitance C_{gs} is a function of V_{GS}.

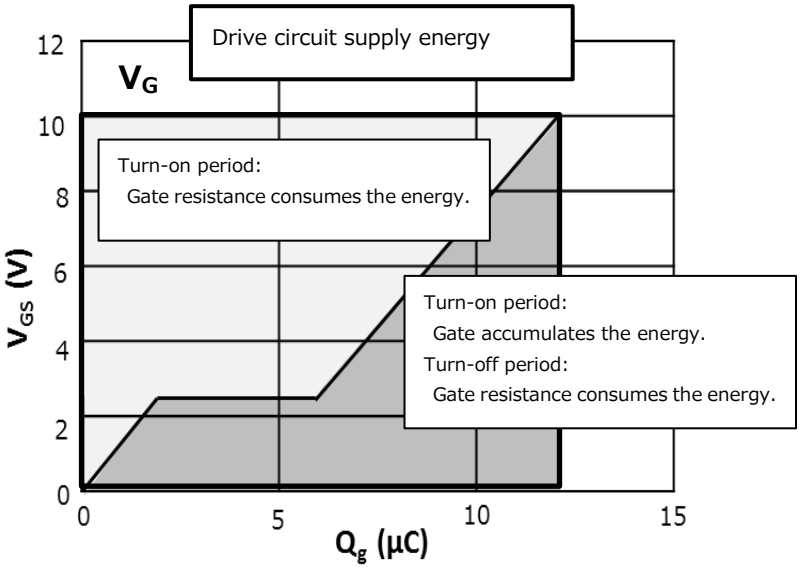


Figure 1.10 MOSFET gate loss

2. Example of a MOSFET gate drive circuit

The basic requirements for a MOSFET drive circuit include an ability to apply a voltage sufficiently higher than V_{th} to the gate and a drive capability to sufficiently charge the input capacitance. This section describes an example of a drive circuit for an N-channel MOSFET.

2.1. Basic drive circuit

Figure 2.1 shows a basic MOSFET drive circuit. In practice, the capacitance of a MOSFET to be driven and its usage conditions must be considered in designing a drive circuit.

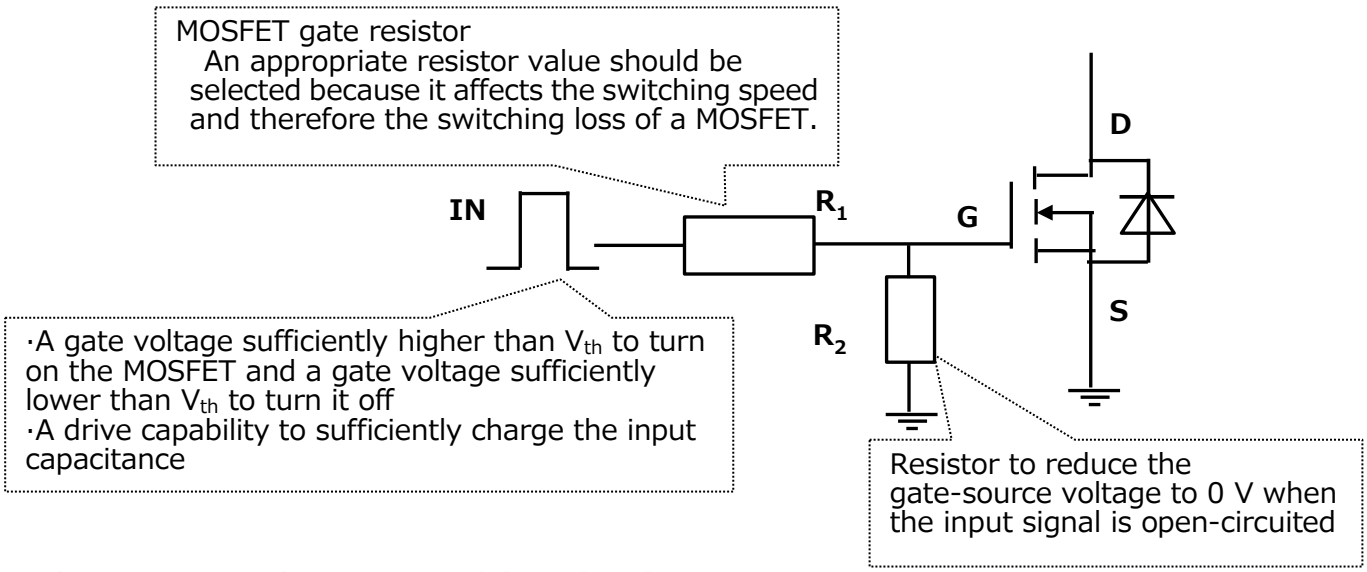


Figure 2.1 Basic MOSFET drive circuit

2.2. Logic drive

There is a growing need for MOSFETs for switching applications (load switches) to provide a conducting path in a circuit only when it is operated, and thereby reduce the power consumption of electronic devices. At present, MOSFETs are directly driven by a logic circuit or a microcontroller in many applications.

Figure 2.2 shows an example of a circuit for turning on and off a power relay. Since turn-on and turn-off times may be as slow as a few seconds for load switches, the MOSFET gate can be driven with a small current.

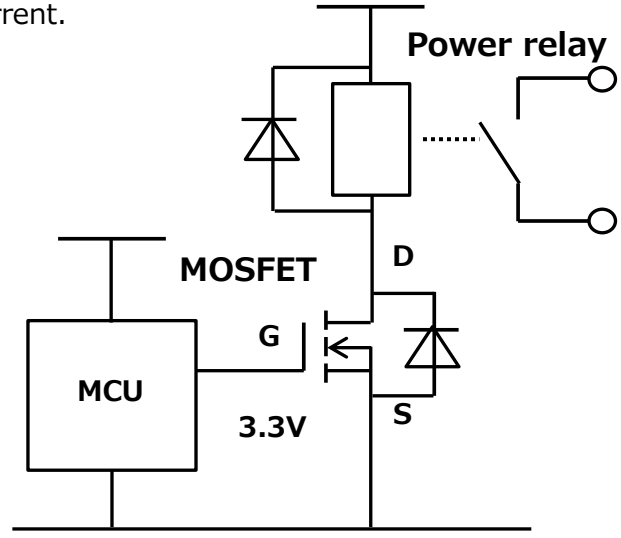


Figure 2.2 Directly driving a MOSFET with an MCU

2.3. Drive voltage conversion

(1) Conversion of a drive voltage to 15 V

Figure 2.3 shows an example of driving a MOSFET with a digital logic. This circuit boosts a drive voltage when the MOSFET cannot be driven at 5 V. R_2 connected in series with the gate resistor R_3 increases the gate drive resistance, making it difficult to drive the MOSFET in saturation mode. This slows the switching speed of the MOSFET and therefore increases the switching loss. On the contrary, reducing R_2 causes a large drain current I_D to flow to the drive circuit during the turn-off period of the MOSFET, increasing the power consumption of the drive circuit.

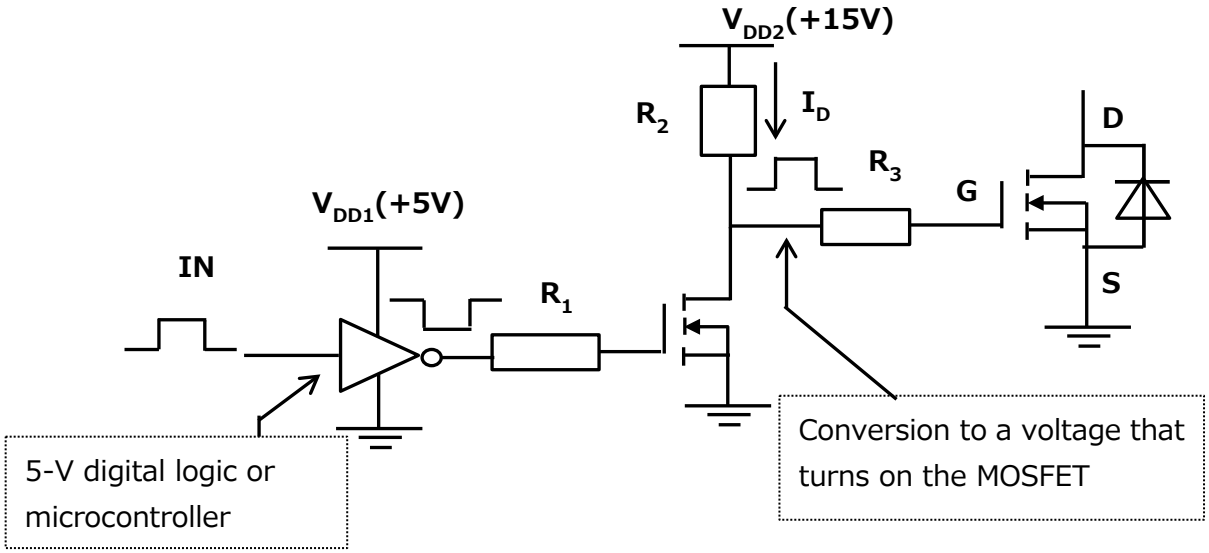


Figure 2.3 Drive voltage conversion

(2) Push-pull circuit

The drawback of the circuit shown in Figure 2.3 is that boosting a drive voltage from digital logic increases the power consumption of the drive circuit. This problem can be solved by adding a push-pull circuit as shown in Figure 2.4.

A push-pull circuit is also used when a drive current for a MOSFET is insufficient.

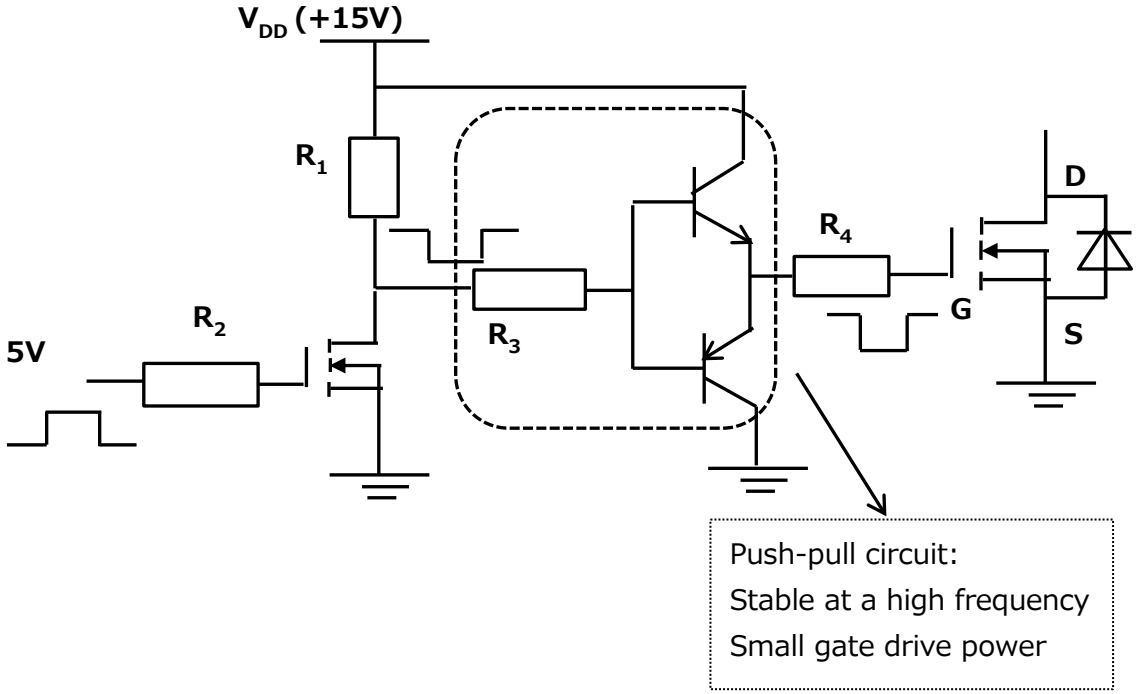


Figure 2.4 Push-pull circuit

2.4. High-side drive from a half or full bridge

Figure 2.5 shows how to use MOSFETs in a half- or full-bridge configuration. To turn on the N-channel MOSFET on the high side Q_1, a higher voltage against source terminal must be applied to its gate terminal.

Since the source voltage of Q_1 varies with the turn-on and turn-off of the low-side MOSFET Q_2, Q_1 and Q_2 cannot share the same ground line of the drive power supply.

2.4.1. Using a high-voltage device and a bootstrap circuit (e.g., high-voltage IC)

Figure 2.5 shows an example of a circuit that drives a high-side device using a high-voltage device and a bootstrap circuit. The switching frequency is limited, depending on the output capacitance and the loss of a level shifter.

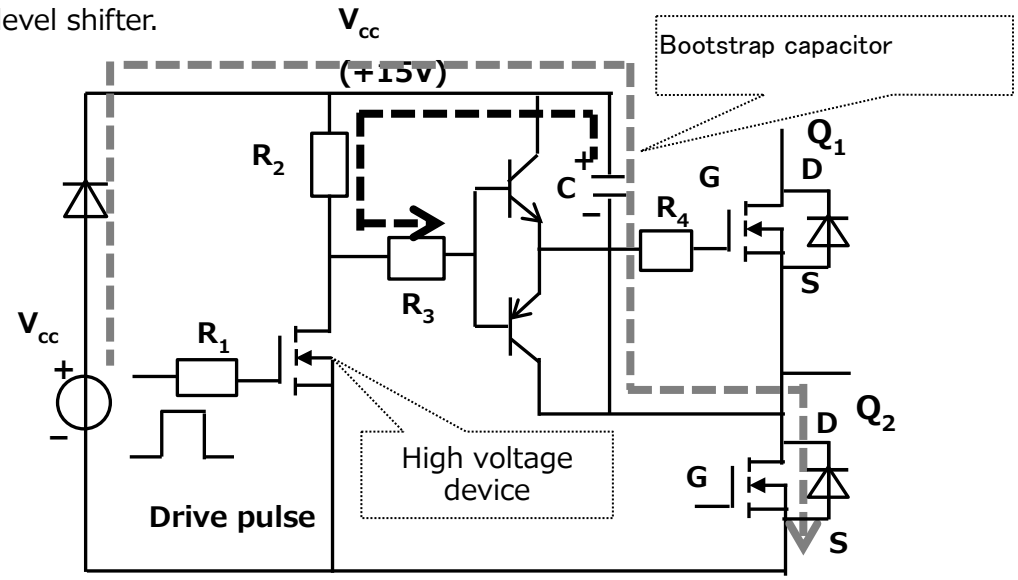


Figure 2.5 High-side drive circuit

2.4.2. Pulse transformer drive (insulated switching)

The use of a pulse transformer eliminates the need for a separate drive power supply. It has a drawback, however, in terms of the power consumption of a drive circuit. A pulse transformer is sometimes used to isolate a MOSFET from its driver in order to protect the drive circuit from the MOSFET's trouble.

Figure 2.6 shows an example of a simple circuit. The purpose of the Zener diode in this circuit is to quickly reset the pulse transformer. The circuit shown in Figure 2.7 has an additional PNP transistor to improve the switching performance.

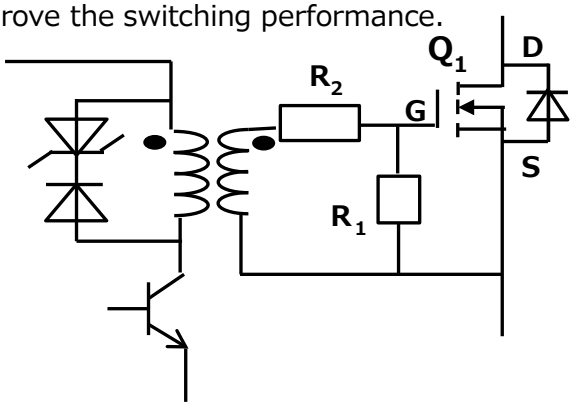


Figure 2.6 Gate drive transformer circuit

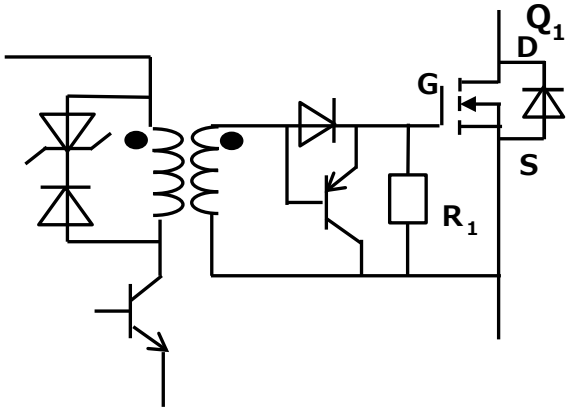


Figure 2.7 Improving the switching performance

The circuit shown in Figure 2.8 has a capacitor in series with a pulse transformer in order to apply a reverse bias to a MOSFET during its turn-off period and thereby improve the switching speed. Since the capacitor blocks the DC bias, it also prevents the pulse transformer from reaching a saturation point.

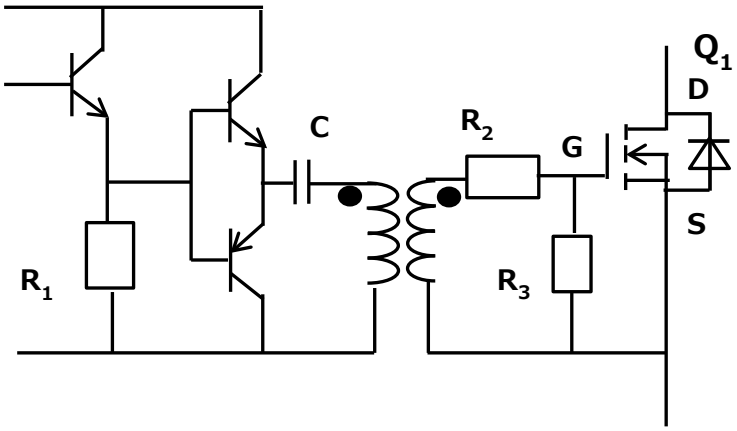


Figure 2.8 Increasing the MOSFET speed

2.4.3. Using a photocoupler and a floating power supply

An optically isolated device (photocoupler) is also used for MOSFET gate drive. A separate power supply is necessary for the photocoupler output. To use a photocoupler to drive the high side of a half or full bridge, a floating power supply is necessary. Care should be exercised as to the speed and drive capability of the photocoupler. Photocouplers specifically designed for MOSFET/IGBT gate drive are available from Toshiba.

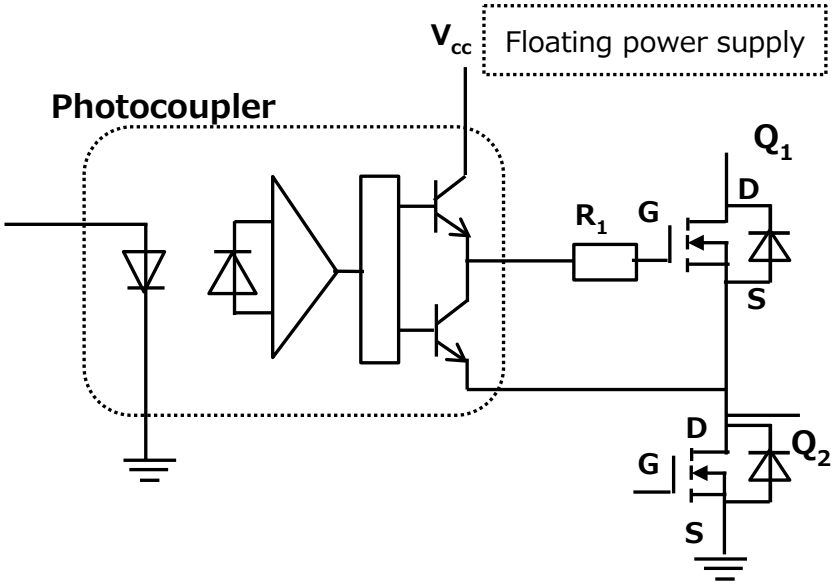


Figure 2.9 Gate drive photocoupler circuit

3. Power supply for the MOSFET drive circuit

3.1. Transformer-isolated power supply

When both the upper and lower arms of an H-bridge, a three-phase inverter or a similar circuit are used to drive MOSFETs, the power supplies for the upper and lower arms must be isolated from each other.

Figure 3.1 shows an example of power supplies using a transformer.

The MOSFETs driven by the lower arm can share the same power supply. Therefore, an H-bridge needs three power supplies whereas a three-phase bridge needs four.

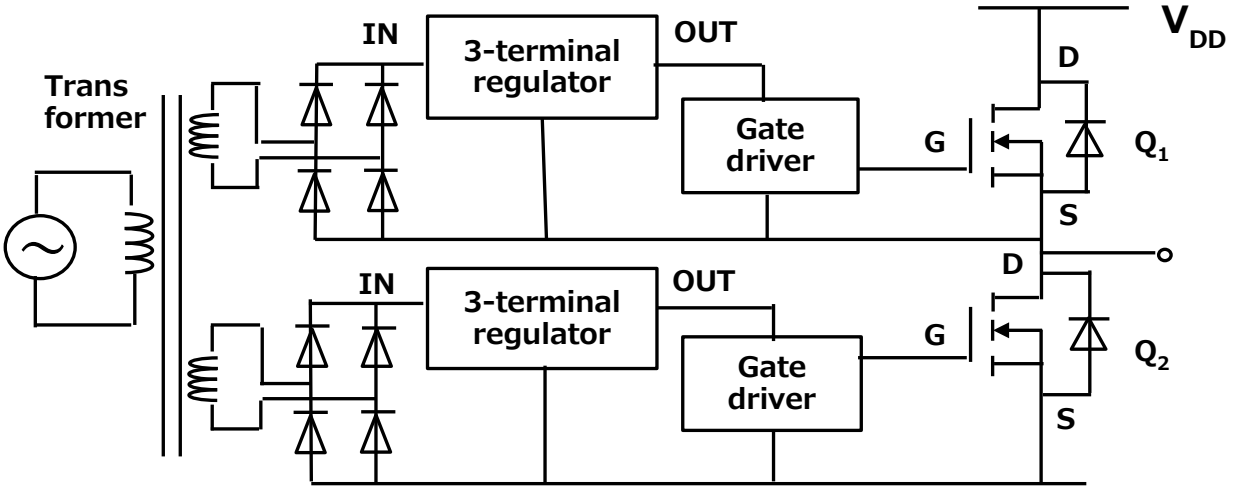


Figure 3.1 Transformer-isolated power supply

3.2. Bootstrap circuit

A bootstrap circuit, which consists of diodes and capacitors, can be used in place of a floating power supply. When MOSFETs are driven by both the upper and lower arms of an inverter or a similar circuit, the bootstrap capacitor C can be used in each phase as shown in Figure 3.2 instead of a floating power supply. Initially, the devices in the lower arm must be turned on to charge capacitor C from the lower-arm power supply through the path highlighted by a dashed line. The capacitor C is charged through this path each time the MOSFET of the lower arm turns on. Since the on-duty cycle of the upper-arm devices has a certain relationship with the amount of charge stored on the capacitor C, there is a limit to the on-duty cycle of the upper arm. As is the case with the output voltage, fluctuations of the gate voltage of the upper arm make it sensitive to noise. Therefore, care should be exercised in designing the upper-arm gate circuit.

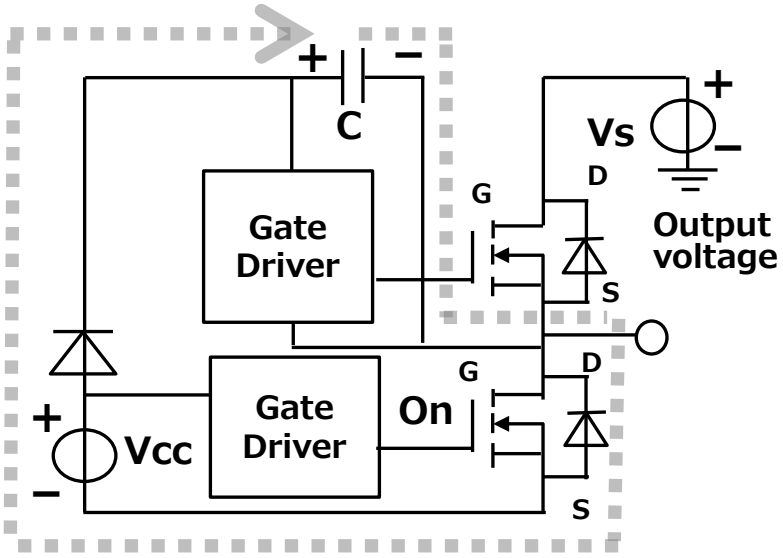


Figure 3.2 Bootstrap circuit

3.3. Charge pump

A charge pump consists of an oscillation circuit, diodes and capacitors. Each stage of a charge pump boosts the voltage stored in the capacitor. The charge pump shown in Figure 3.3 can be used to drive the high side when MOSFETs are driven by both the upper and lower arms. Unlike a bootstrap circuit, the charge pump does not impose any limit to the duty cycle of the output device.

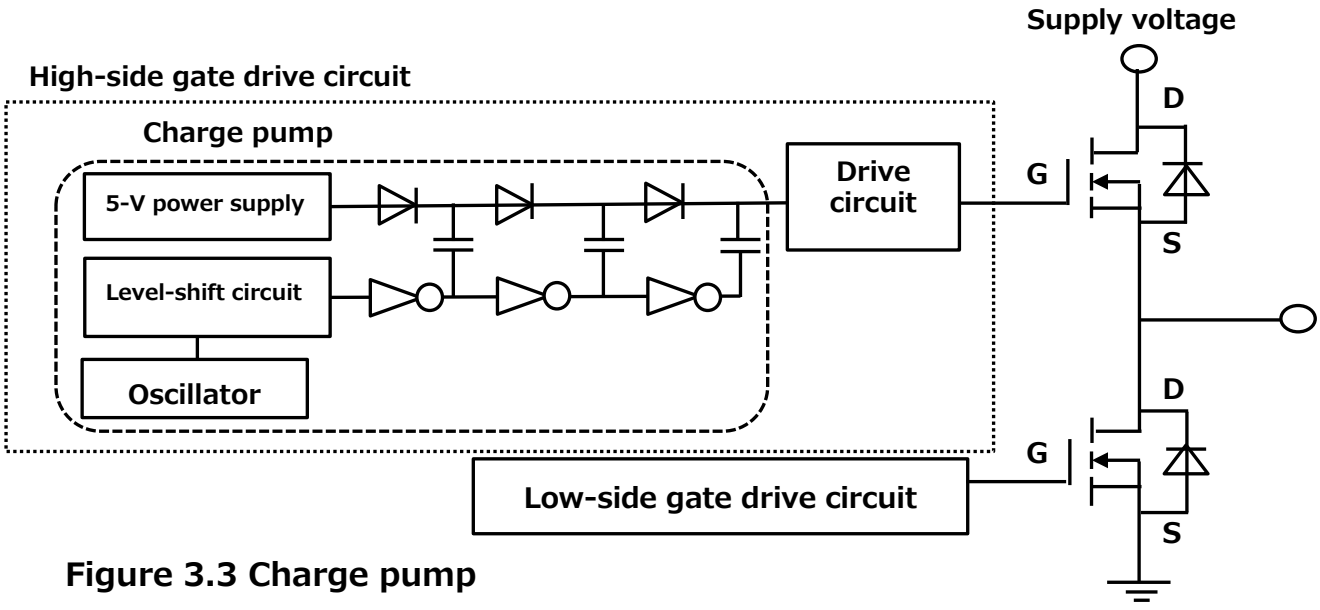


Figure 3.3 Charge pump

4. Considerations for the MOSFET drive circuit

4.1. Considerations for the gate voltage V_{GS} conditions

V_{GS} is important for MOSFET gate drive.

The on-state resistance of MOSFETs is low when they operate in the linear region (i.e., at a voltage lower than pinch-off voltage).

Therefore, for switching applications, you can reduce the on-state resistance by using MOSFETs in the low V_{DS} region.

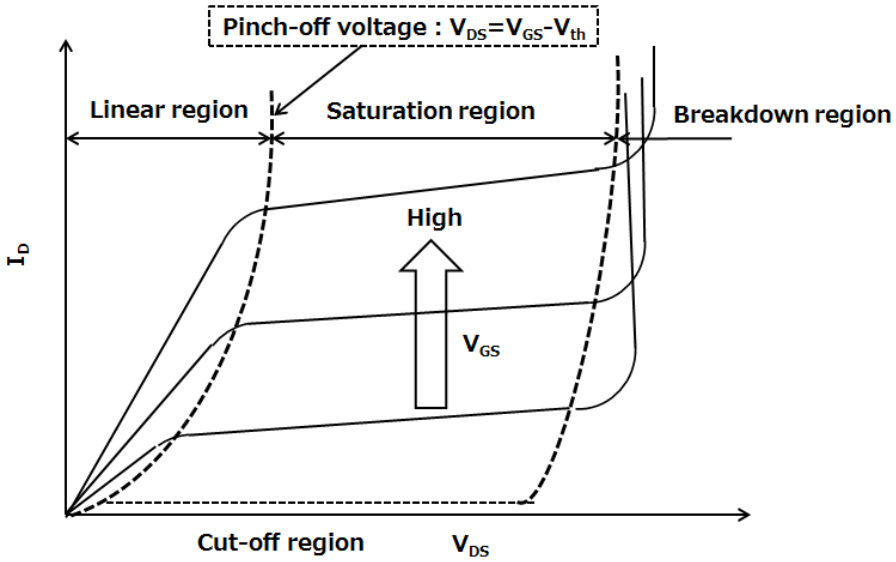


Figure 4.1 Operating Regions of a MOSFET

· A MOSFET turns on when its gate voltage V_{GS} exceeds its threshold voltage V_{th} as shown in Figure 4.2. Therefore, V_{GS} must be sufficiently higher than V_{th}.

· The higher the V_{GS}, the lower the $R_{DS(ON)}$ value tends to become.

· The higher the temperature, the higher the $R_{DS(ON)}$ value becomes (Figure 4.3).

· In order to reduce loss, it is important to increase V_{GS} in order to minimize the resistance of the device at the current level at which it is used (Figure 4.4). Conversely, a high V_{GS} value increases the ratio of drive loss to the total loss for high-frequency switching.

Selecting the optimal MOSFET and gate drive voltage is therefore critical. For many of Toshiba's power MOSFETs, it is generally recommended to drive their gates at a V_{GS} of 10 V. Toshiba's product portfolio also includes power MOSFETs designed for gate drive at a V_{GS} of 4.5 V. Select the power MOSFET that best suits your system requirements.

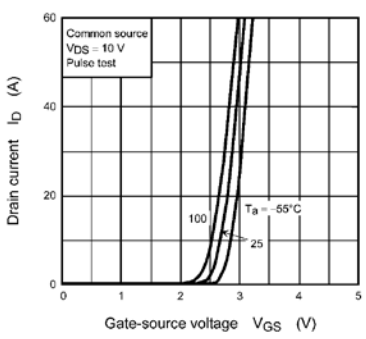


Figure 4.2 I_D – V_{GS} curves

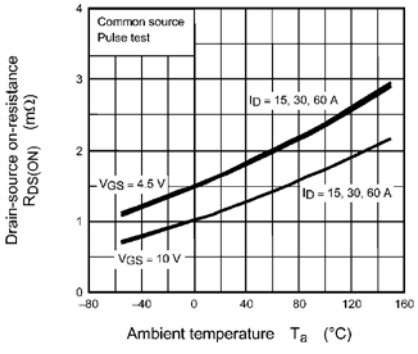


Figure 4.3 $R_{DS(ON)}$ vs. temperature

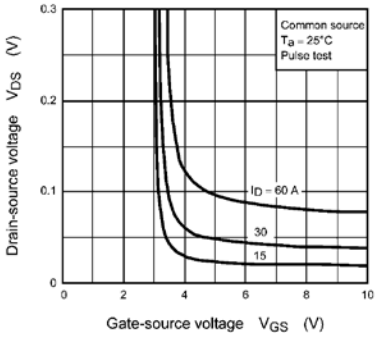


Figure 4.4 V_{DS}-V_{GS} curves

4.2. Gate voltage, peak current and drive loss

In designing a drive circuit for a MOSFET, a drive loss and a current for charging the gate input capacitance are very important as described in Section 1.3, "Gate drive power."

Since $Q_g = \int i_G \, dt$, the average gate inrush current, i_G(rush), during the switching period is expressed as:

$$i_G(\text{rush}) = Q_g / t_{sw}$$

A drive loss can be calculated as:

$$P_G = E \times f_{sw} = V_G \times Q_{gp} \times f_{sw}$$

Increasing the gate voltage reduces $R_{DS(ON)}$ and therefore the steady-state loss. However, since Q=CV, increasing the gate voltage increases Q_g and therefore the gate current and the drive loss. When MOSFETs switch at a high frequency in light-load applications, the gate drive losses significantly affect their total loss. Care should be exercised in designing a drive circuit.

4.3. Gate resistors and switching characteristics

Generally, a resistor is connected to the gate terminal of a MOSFET. The purposes of the gate resistor include suppression of inrush current and a reduction in output ringing. A large gate resistor decreases the switching speed of a MOSFET. This results in an increase in power loss, a reduction in performance and potential heat issues. Conversely, a small gate resistor increases the switching speed of a MOSFET, which makes it susceptible to voltage surge and oscillation and therefore to device failure and damage. It is therefore important to optimize the MOSFET switching speed by adjusting the gate resistor value.

The gate rise time t_g and the gate resistor value R_G have the following relationships:

$$Q_g / t_g = i_G$$

$$R_G = V_G / i_G$$

We considered the switching waveform of a MOSFET for the circuit shown in Figure 4.5 using simulation. In order to estimate an actual circuit, a wire stray inductance was inserted in the simulation circuit. The magnitude and period of output ringing depend on stray inductance.

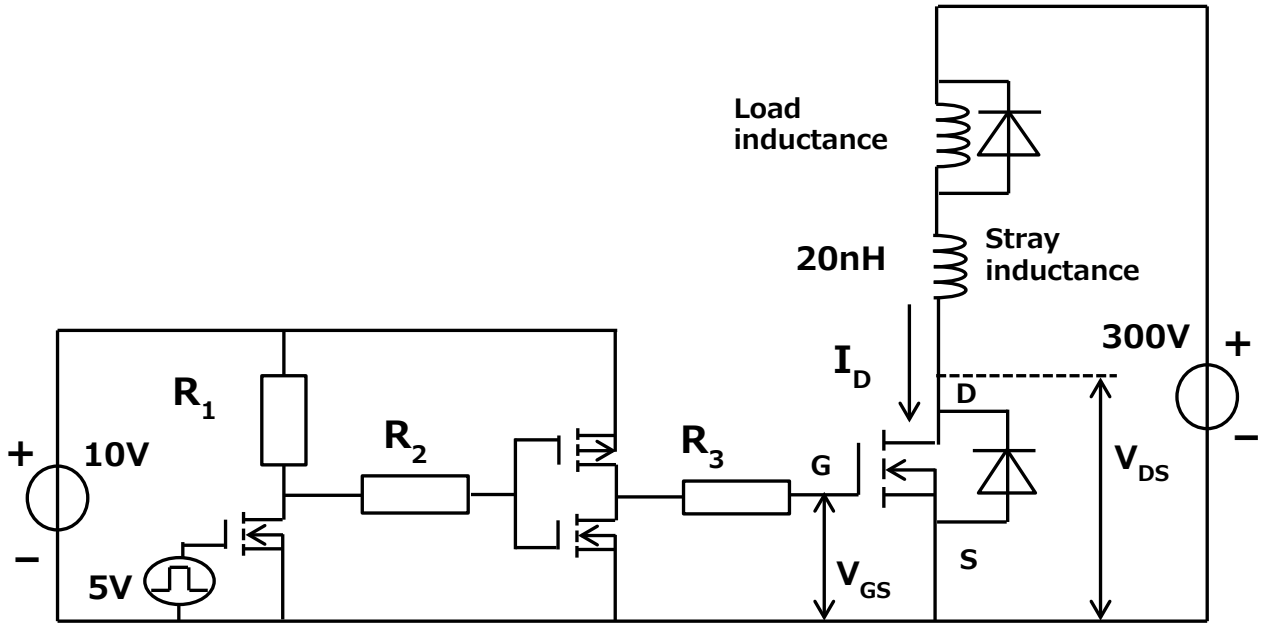


Figure 4.5 Switching simulation circuit

We simulated to obtain the switching-off waveforms of the circuit shown in Figure 4.5, changing the gate resistor R_3 to 1, 10 and 50. Figure 4.6 shows the simulation results. As described above, reducing the gate resistor value increases the switching speed of a MOSFET at the expense of an increase in the ringing voltage. Conversely, increasing the gate resistor value reduces the ringing voltage, but reduces the switching speed of a MOSFET and therefore increases its switching loss. This is because the gate resistor value and the gate voltage restrict the gate charge current of a MOSFET.

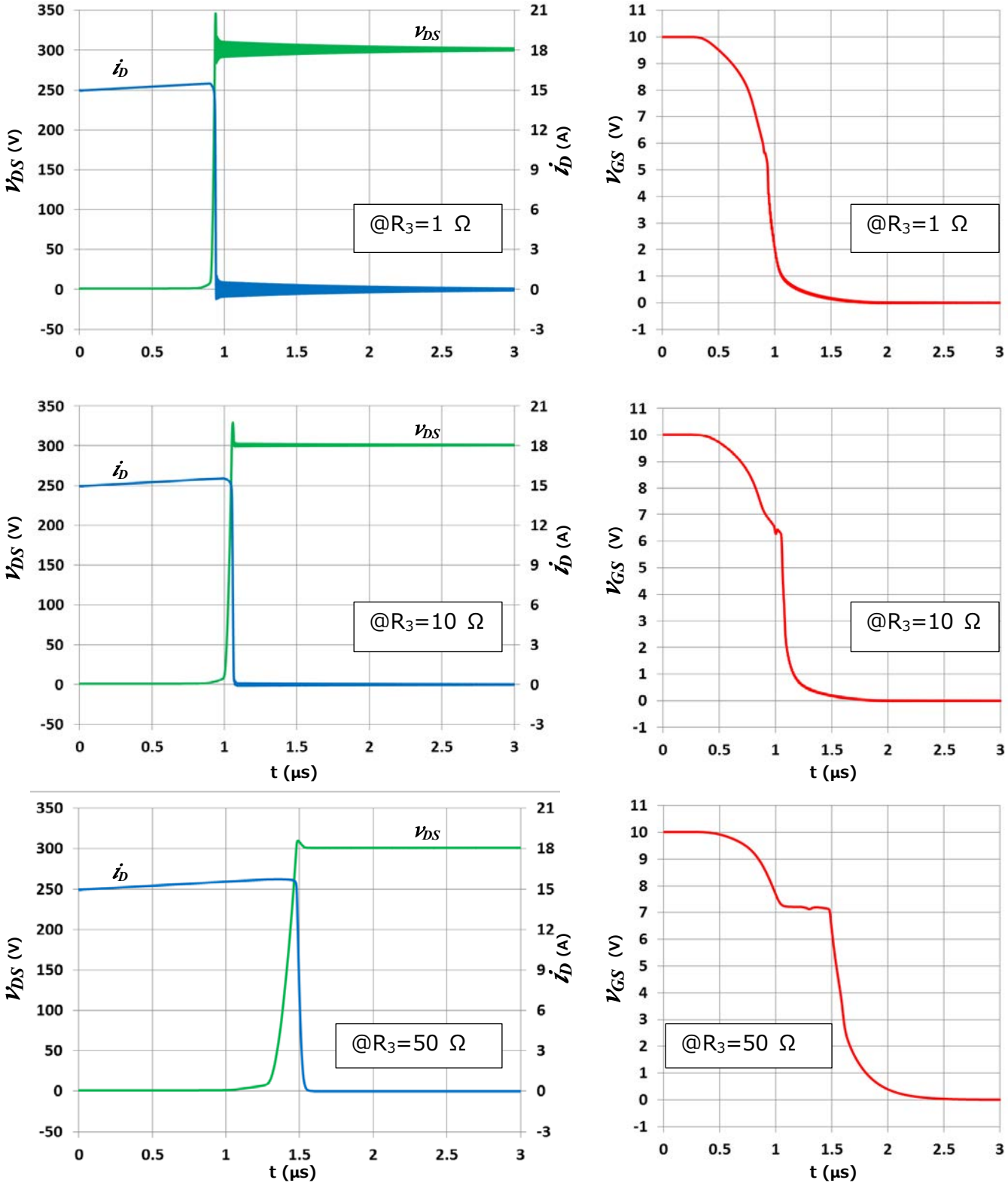


Figure 4.6 Switching-off waveforms

4.4. Considerations for gate drive

4.4.1. Protection against gate-emitter surge voltage

Adding an external Zener diode between the gate and source terminals of a MOSFET is effective for protection against electrostatic discharge and gate surge voltage. Note, however, that the capacitance of the Zener diode might have a slight adverse effect.

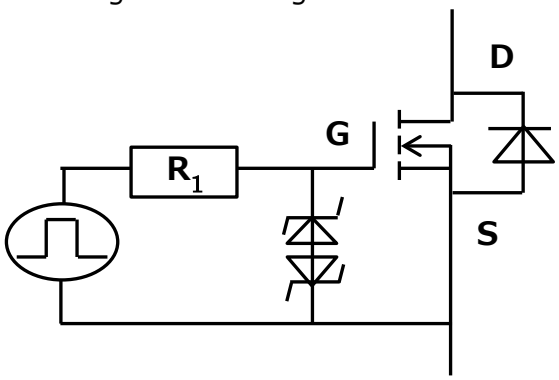


Figure 4.7 Protection against gate surge voltage

4.4.2. Optimal gate resistor

As discussed in Section 4.3, “Gate resistors and switching characteristics,” the switching speed varies with the gate resistor value. Increasing the gate resistor value slows the switching speed of a MOSFET and increases its switching loss. Reducing the gate resistor value increases the switching speed of a MOSFET, but might cause a surge voltage to be applied between its drain and the source terminals due to the effects of wire stray inductance and other factors.

It is therefore necessary to select the optimal gate resistor. Sometimes, different gate resistors are used for the turn-on and turn-off of a MOSFET. Figure 4.8 shows an example of how to use different gate resistors for turn-on and turn-off.

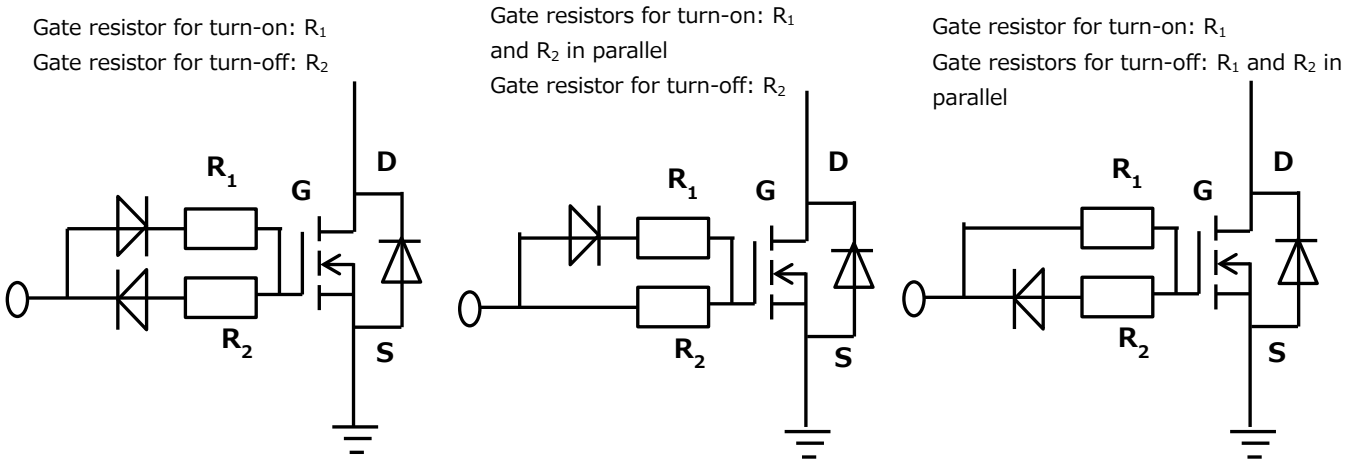


Figure 4.8 Gate resistors

4.4.3. Gate malfunction prevention

One of the problems with MOSFETs is the parasitic turn-on (self-turn-on) phenomenon caused by their drain-gate capacitance. Upon turn-off, a sharp dv/dt develops between the source and the drain of a MOSFET. The resulting current flows to the gate via the drain-gate capacitance. As a result, a voltage drop that occurs across the gate resistor lifts the gate voltage. This current is calculated as:

$i_{DG} = C_{gd} \cdot dv_{DS} / dt$

Figure 4.9 shows the current path.

If dv/dt has a very sharp slope, a voltage is applied to the gate of a MOSFET, depending on the ratio of the gate-source capacitance to the gate-drain capacitance. If this occurs, self-turn-on might occur.

Self-turn-on could also occur when a rapidly changing voltage is applied to a MOSFET in the off state during diode reverse recovery.

There are three ways to prevent the self-turn-on phenomenon:

(1) Adding a capacitor between the gate and source terminals

The capacitor inserted between the gate and source terminals absorbs the drain-gate current caused by dv/dt. This circuit is shown in Figure 4.10. Since the gate-source capacitor is connected in parallel with C_{gs} inside the MOSFET, the gate charge increases. If the gate voltage is fixed, you can keep the switching speed of the MOSFET unchanged by changing the gate resistor value, but this increases the drive power consumed.

(2) Miller clamp circuit

The Miller clamp circuit shorts the path between the gate and source terminals of a MOSFET using a switching device. This can be realized by adding another MOSFET between the gate and source terminals of the MOSFET concerned. In Figure 4.11, if a voltage falls below a predefined voltage lower than the Miller voltage, a comparator provides a logic High, turning on the MOSFET between the gate and source terminals. This, in turn, short-circuits the gate-source path of the output MOSFET and suppresses the lifting of the gate voltage caused by a current through the feedback capacitor C_{rss} and the gate resistor.

(3) A turn-off gate voltage can be driven to a negative value so that it will not exceed V_{th}. However, this method requires a negative power supply.

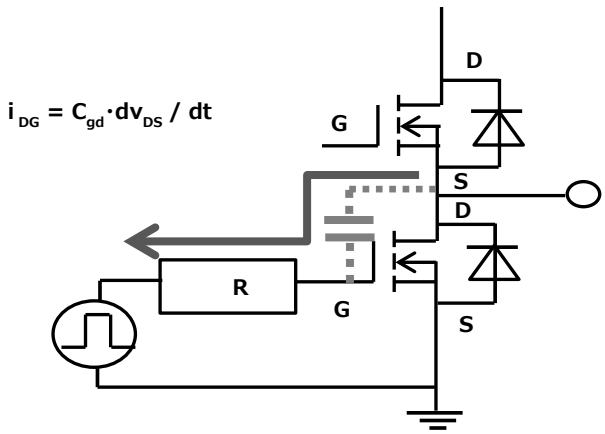


Figure 4.9 Mechanism of a gate malfunction

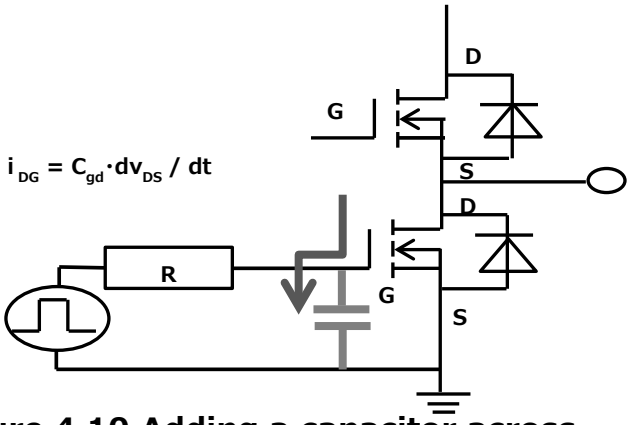


Figure 4.10 Adding a capacitor across the gate and source terminals

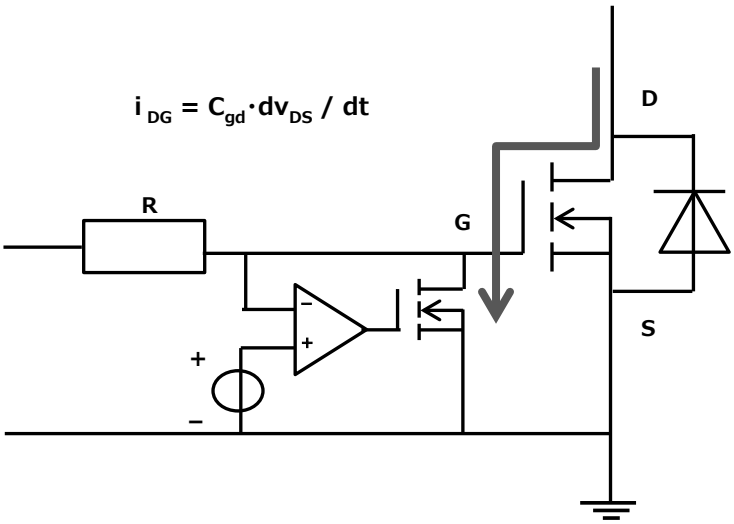


Figure 4.11 Miller clamp circuit

We simulated a self-turn-on phenomenon using the circuit shown in Figure 4.12. Self turn-on is induced by i_{DG} (dv/dt current) and gate resistance and causes a false turn-on.

In reverse recovery mode, if Q_2 turns on while the inductor load current is flowing back through the diode of Q_1, an inductor current flows through Q_2, causing the associated diode to turn off. We examined what occurs when a high dv/dt voltage is applied to a MOSFET in the off state. In order to force a self-turn-on phenomenon to occur, only the gate resistor R_4 associated with Q_1 was changed in Figure 4.12.

Figure 4.13 shows waveforms without a self-turn-on phenomenon and Figure 4.14 shows waveforms with a self-turn-on phenomenon.

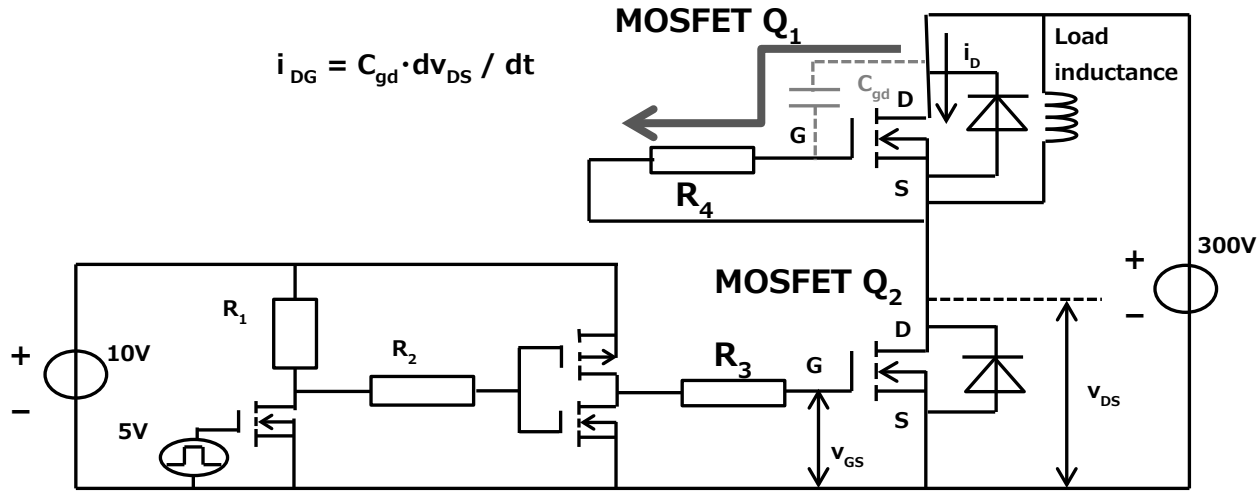


Figure 4.12 Test circuit for self-turn-on waveforms

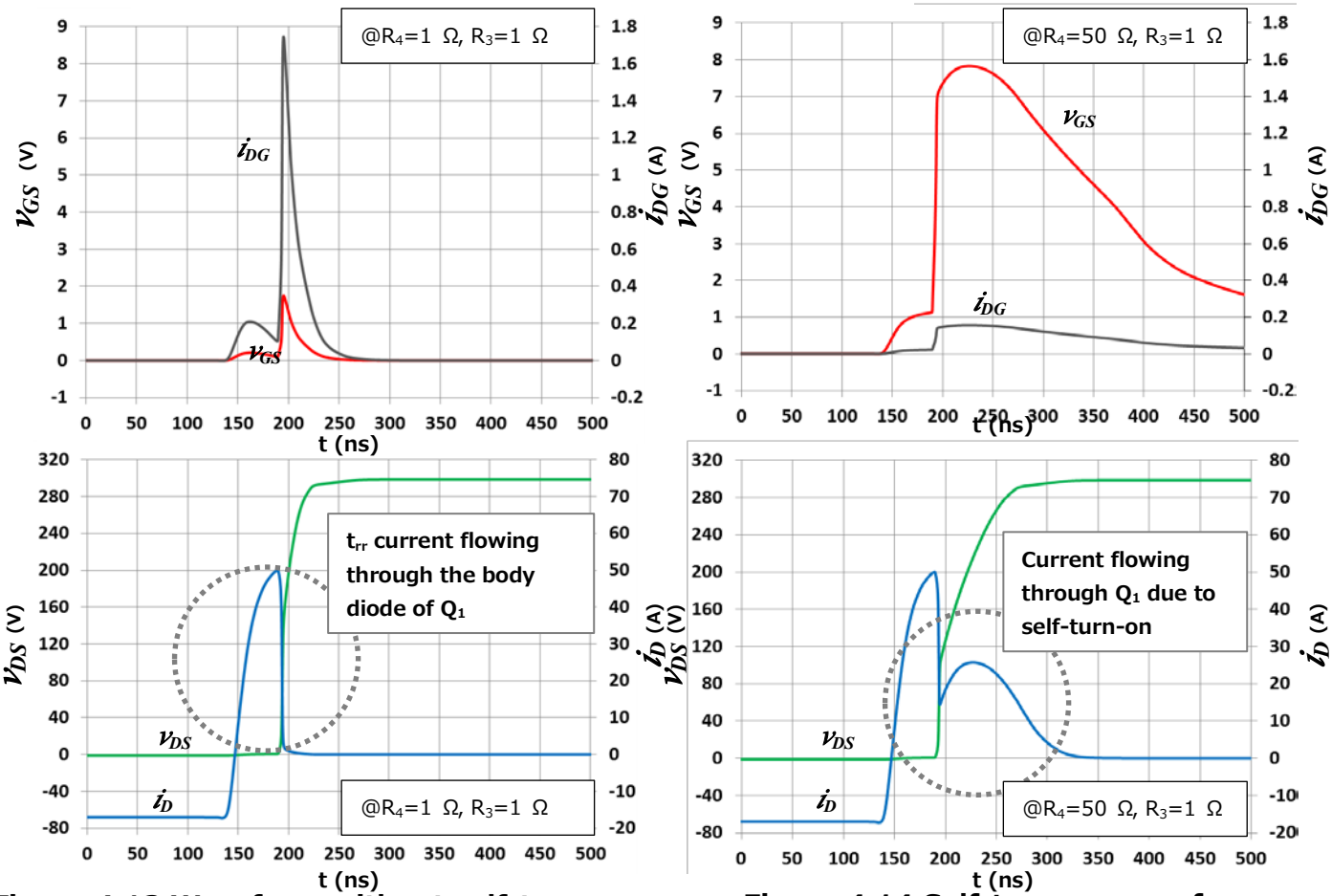


Figure 4.13 Waveform without self-turn-on

Figure 4.14 Self-turn-on waveform

Next, as shown in Figure 4.15, we added a capacitor between the gate and source terminals of the MOSFET Q_1 to the circuit shown in Figure 4.12. The purpose of this capacitor is to absorb a gate current ($C_{gd} \cdot dv_{DS} / dt$) in order to reduce a gate voltage due to the gate resistor and thereby reduce self-turn-on voltage.

Figure 4.16 shows the improved waveform. Since the addition of the gate-source capacitor changes the MOSFET switching time, its capacitance and the gate resistance should be adjusted together.

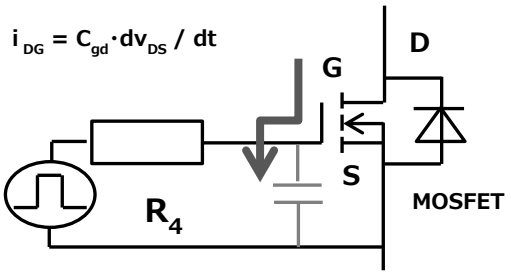


Figure 4.15 Adding a capacitor across the gate and source terminals

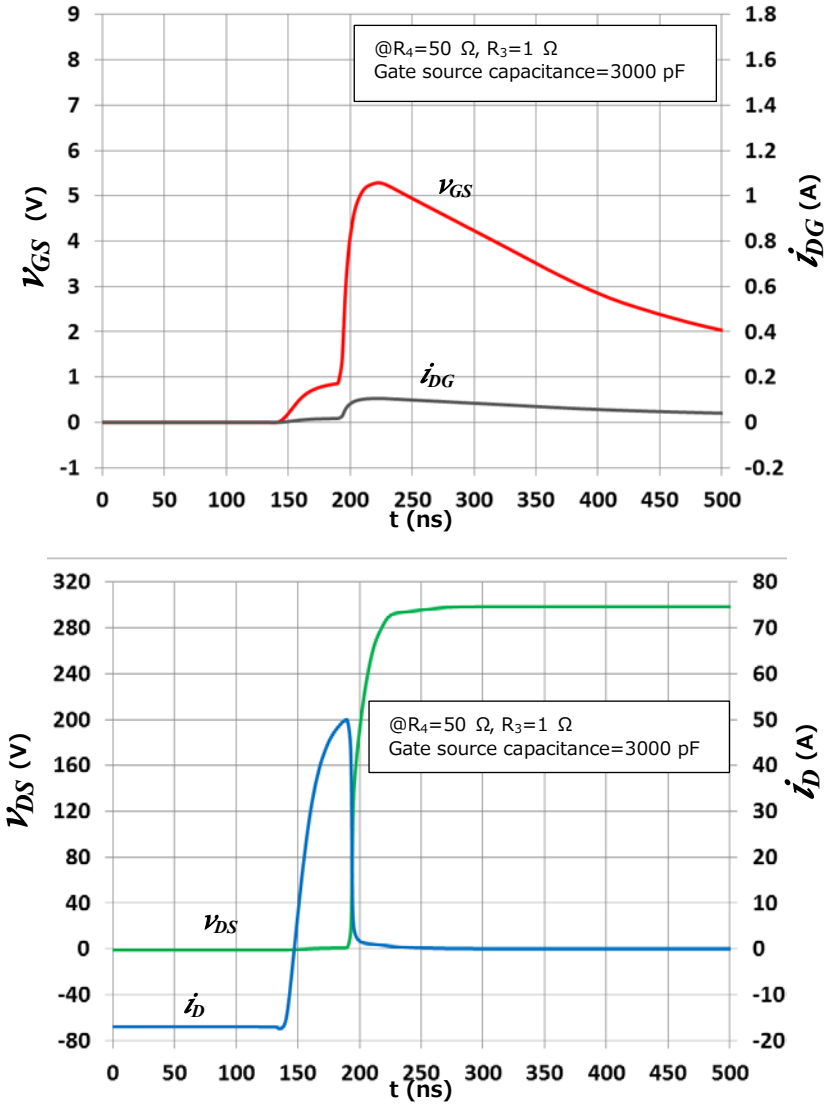


Figure 4.16 Improved self-turn-on waveform

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