SiC MOSFET

Snubber circuit design methods

SiC MOSFET is getting more popular in applications where fast and efficient switching is required, such as power supply applications. On the other hand, the fast switching capability causes high dv/dt and di/dt, which couple with stray inductance of package and surrounding circuit, resulting in large surge voltage and/or current between drain and source terminals of the MOSFET. The surge voltage and current have to be controlled to not exceed the maximum rated voltage/current of the device. This application note illustrates a way to design snubber circuit, which is one of the methods to suppress surges voltages and currents.

Surge voltage occurring in Drain-Source

When a MOSFET turns on, current stores energy in the stray inductance of the wire on the PCB layout. The stored energy resonates with the parasitic capacitance of the MOSFET, and that produces surge current. Figure 1 illustrates the path of the 'ringing current' in a half bridge topology, which has high side switch (HS) and low side switch (LS). When LS turns on, current I_{MAIN} flows from V_{SW} through the stray inductance L_{MAIN}.
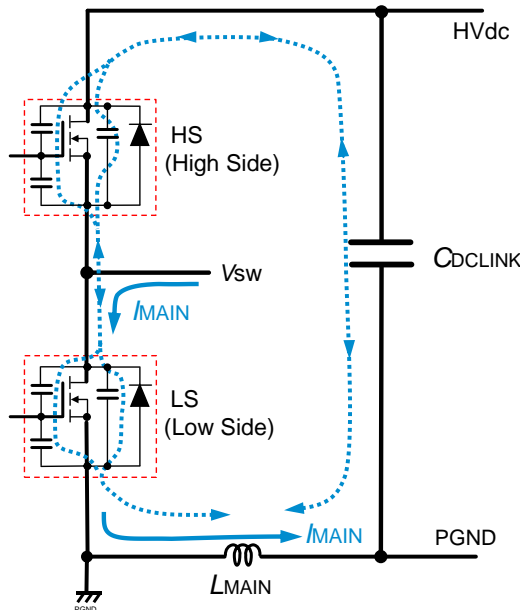
When LS turns off, I_{MAIN} flows through the loop form by L_{MAIN}, C_{DCLINK} and parasitic capacitance of HS and LS, as shown by dotted line. Where C_{DCLINK} is bulk capacitor placed in parallel with input HVdc-PGND. During the turn off of LS, surge voltage occurs in drain-source of LS by resonant phenomenon between L_{MAIN} and parasitic capacitance of the MOSFET C_{OSS} ($C_{DS}+C_{DG}$). The maximum voltage V_{DS_SURGE} is as shown in (1). Where V_{HVDC} is the applied voltage on HVdc terminal and R_{OFF} is resistance when the MOSFET turns off. [*1].

$$V_{DS\_SURGE} = \frac{V_A * e^{-(a/\omega)[\tan^{-1}(a/\omega)+\Phi]}}{1+(a/\omega)^2} + V_{HVDC} \qquad (1)$$

where:

$$V_A = \sqrt{V_{HVDC}^2 + (a/\omega)^2 * \left(2 * R_{OFF} * I_{MAIN} - V_{HVDC}\right)^2}$$

$$\Phi = \tan^{-1}\frac{V_{HVDC}}{(a/\omega)*(2*R_{OFF}*I_{MAIN}-V_{HVDC})}$$

$$a = \frac{1}{2*R_{OFF}*C_{OSS}}$$

$$\omega_{SURGE} = \frac{1}{\sqrt{L_{MAIN}*C_{OSS}}} * \sqrt{1 - (\frac{\sqrt{L_{MAIN}/C_{OSS}}}{2R_{OFF}})^2}$$

Figure 1 Current path when turn-off surge occurs

Figure 2 shows surge waveforms when ROHM's SiC MOSFET (SCT2080KE) turns off with 800V applied on HVdc. According to the waveform, V_{DS_SURGE} reaches 961V and ringing frequency is about 33MHz, which brings L_{MAIN} of 110nH.
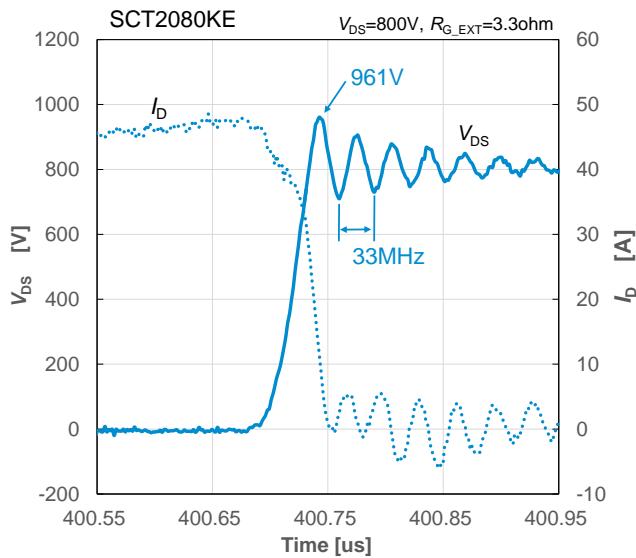
Figure 2. Turn-off waveform with surge

It would be the best if stray inductance is minimized as much as possible. However it is not always realistic because it might make the heat dissipation condition worse. Instead, placing the snubber capacitor as close as possible to the MOSFET minimize the stray inductance of the circuit. The snubber capacitor also absorbs the energy stored in the minimized connection inductance and clamps surge voltage while the MOSFET turns off.

Next step, a snubber capacitor C_{SNB} is introduced, as shown in Figure 3. This capacitor makes L_{MAIN} neglectable. The waveform of the surge voltage when LS turns off is shown in Figure 4.
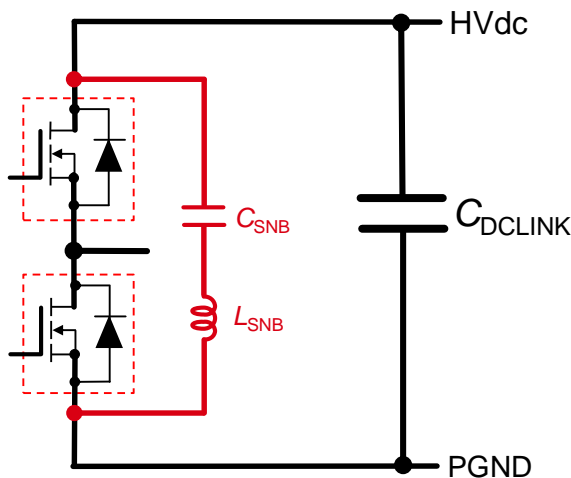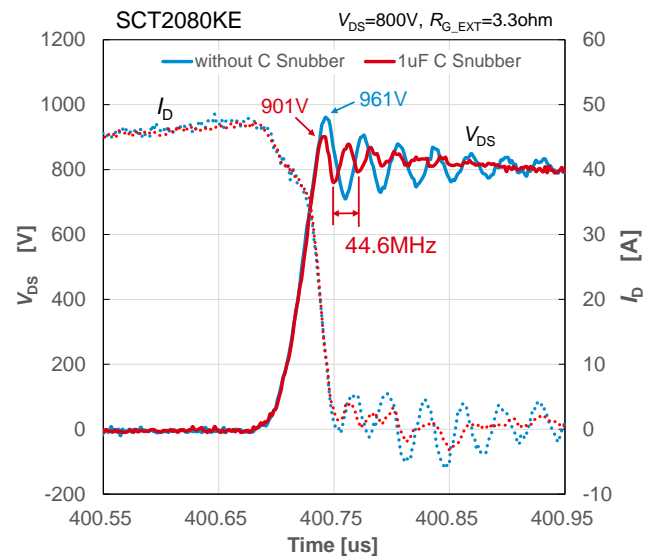

Figure 4. Reducing turn-off surge by C snubber

Figure 3 C Snubber

Variety and selection of snubber

There are two methods of snubber circuits: passive snubber, which consists of passive components such as resistor, inductor, capacitor and diodes; and active snubber, which utilize semiconductor switch[*1]. In this application note, passive snubber is chosen, due to its simplicity and cost effectiveness.

Figure 5 shows different snubber examples: (a) C snubber, where the capacitor C_{SNB} is connected in parallel to the MOSFET bridge; (b) RC snubber where the resistor R_{SNB} and capacitor C_{SNB} are connected in parallel to each MOSFET; (c) Discharge RCD snubber, where a diode is added to RC snubber; and (d) non-discharge RCD snubber, where the discharging path is changed from the discharge RCD snubber presented in (c).

Surge voltage is reduced by more than 50V (reaching 901V) and ringing frequency increases to 44.6MHz. It is because C_{SNB} is placed close to the switches and as a result, the stray inductances (L_{SNB}) involved in the switching path is reduced. In this case, L_{SNB} is about 71nH according to the equation (1).

In principle, the snubber has to be placed as close as possible to the MOSFET in order to maximize its effectiveness.

(a) C snubber: it has fewer components but has relatively longer wires. It is more suitable for 2in1 module rather than circuit with discrete components.

(b) RC snubber: it can be placed close to the MOSFET, however the energy stored in C_{SNB} has to be dissipated by R_{SNB} during every switching transient of the MOSFET. If the switching frequency is high enough, R_{SNB} would dissipate large amount of energy (several watts), which limits the size of C_{SNB}. And, as results, the suppressing surge capability of the snubber is reduced.

(a)   (b)
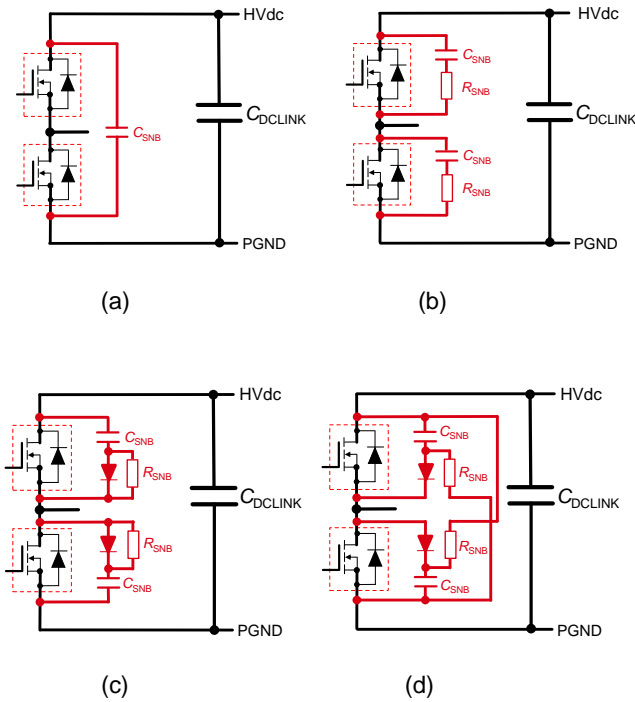

(c)   (d)

Figure 5 Snubber circuits

(a) C snubber, (b) RC snubber,

(c) Discharge RCD snubber, (d) Non-discharge RCD snubber

(c) Discharge RCD snubber: R_{SNB} dissipates energy as much as in (b) during turn ON, but C_{SNB} surge absorption capability is more effective than (b) because surge current flows through the diode. The recovery characteristic of the diode must be considered, high di/dt in the snubber circuit can be occurred during the switching transient. Therefore, stray inductances should be minimized as much as possible to limit over voltages. It is also the same effect if R_{SNB} is connected with C_{SNB} in parallel.

(d) Non-discharge RC snubber: R_{SNB} dissipates only the energy absorbed by C_{SNB} produced during the overvoltage, it means the snubber doesn't discharge all energy stored in C_{SNB} at every switching transient. Thus the energy consumption at R_{SNB} does not much increase at high switching frequencies. Therefore a large C_{SNB} can be implemented, which realizes a highly effective snubber circuit. But it is also to be noted that this method requires very complicated wire layout which can be realized by more than 4 layers PCB.

Every snubber circuit has both advantages and disadvantages, and should be chosen according to circuit topology and power.

Designing C snubber

C snubber circuit (Figure 6) absorbs energy stored at L_{MAIN}. The stray inductance of the snubber path L_{SNB} has to be less than L_{MAIN}. Larger C_{SNB} makes snubber more effective because energy stored at C_{SNB} is not discharged. Series inductance of the capacitor (ESL), which adds on L_{SNB}, has to be minded because ESL normally increases with the capacitor size.

Capacitor should be selected based on electrostatic capacity calculated using eq. (2). V_{DC_SURGE} is defined as the maximum surge of HVdc. With an assumption that all energy stored at L_{MAIN} is transferred to C_{SNB}.

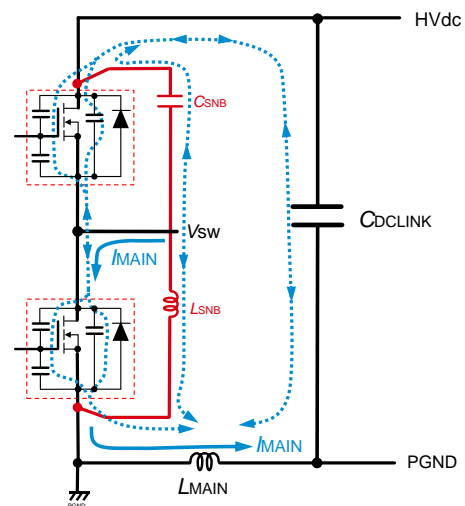$$C_{SNB} > \frac{L_{MAIN} * I_{MAIN}^2}{V_{DS\_SURGE}^2 - V_{HVDC}^2} \qquad (2)$$

Figure 6 C snubber

Designing RC snubber

Figure 7 shows the current loops when RC snubber works. C_{SNB} is determined by equation (2) and R_{SNB} is obtained from equation (3).

$$R_{SNB} < \frac{-1}{f_{SW}*C_{SNB}*\ln[(V_{DS\_SURGE}-V_{SNB})/V_{DS\_SURGE}]} \quad (3)$$

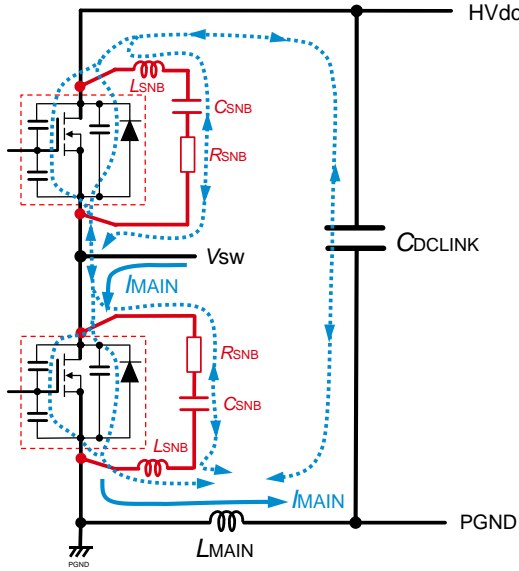

Figure 7 RC snubber

Where:

- f_{SW}: Switching frequency, and
- V_{SNB}: Discharge voltage of snubber (0.9x V_{DS_SURGE})

After determining the value of R_{SNB}, the resistor size has to be selected based on the power dissipation calculated by equation (4).

$$P_{SNB} = \frac{L_{TRACE}\times I_{MAIN}{}^2\times f_{sw}}{2} + \frac{C_{SNB}\times V_{HVDC}{}^2\times f_{sw}}{2} \quad (4)$$

This equation says that, the higher the f_{SW} or V_{HVDC} the higher the power dissipation of R_{SNB} must be. In case of P_{SNB} is too high for the resistor, C_{SNB} needs to be decreased.

In addition, resonant frequency ω_{SNB} of R_{SNB} and C_{SNB} has to be lower enough than resonant frequency of surge ω_{SURGE}, as presented by (5). Thus the RC snubber can absorbs surge voltage.

$$\omega_{SNB} = \frac{1}{R_{SNB}*C_{SNB}} \ll \omega_{SURGE} \quad (5)$$

Designing discharge RCD snubber

Design procedure of discharge RCD snubber is basically the same as RC snubber. Besides resonant frequency is not need to be minded because surge is absorbed by Diode. For diode, a fast recovery diode type is suitable.

Designing non-discharge RCD snubber

Non-discharge RCD snubber only consumes energy from the surge voltage, as a result the power dissipation of R_{SNB} is reduced and the selection options for R_{SNB} is wider. Thus, C_{SNB} can be increased, and therefore, the clamping effectiveness.

C_{SNB} and R_{SNB} are determined by equation (2) and (3) respectively. Power consumption of R_{SNB} is determined by following equation (6) which does not have the second term of equation (4) including C_{SNB} and f_{sw}. This leads efficient clamping capability and makes higher frequency of f_{sw} possible.

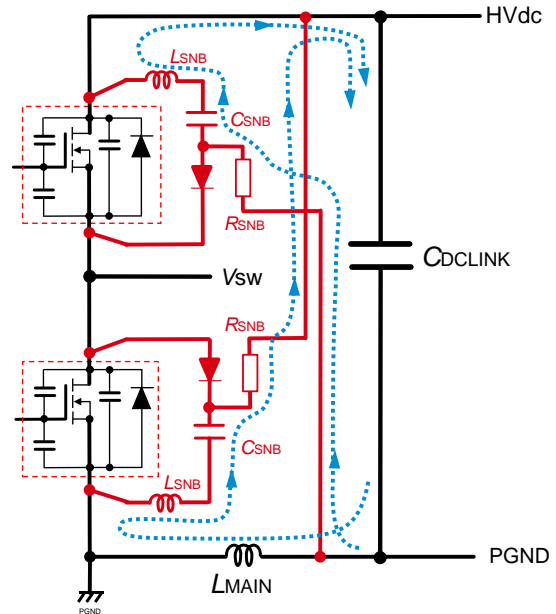$$P_{SNB} = \frac{L_{TRACE}\times I_{MAIN}{}^2\times f_{sw}}{2} \quad (6)$$


Figure 8. Discharging route of non-discharge RCD snubber

Figure 8 shows discharging route right after snubber action of non-discharge RCD type. The discharging current flows in the upper arm to PGND and in lower arm to HVdc through R_{SNB}, which is not highly influenced by the wire inductance. On the other hand, wire inductance L_{SNB} has to be as small as possible to avoid over voltages due to the high di/dt.

Figure 9 shows turn-off surge comparison both V_{DS} and I_D. (a) is a test circuit and (b) is the V_{DS} and I_D during the turn-off transient of the MOSFE.T. The experimental results have been obtained using ROHM's evaluation board (part number P02SCT3040KR-EVK-001) with SiC MOSFET (SCT3080KR) to verify effectiveness of the non-discharge RCD snubber. The test have been performed with a R_{G_EXT} =3.3Ω, E =800V and drain current I_D =ca.70A.
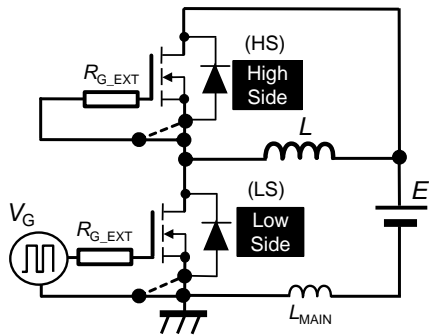
(a) Circuit of double pulse switching test
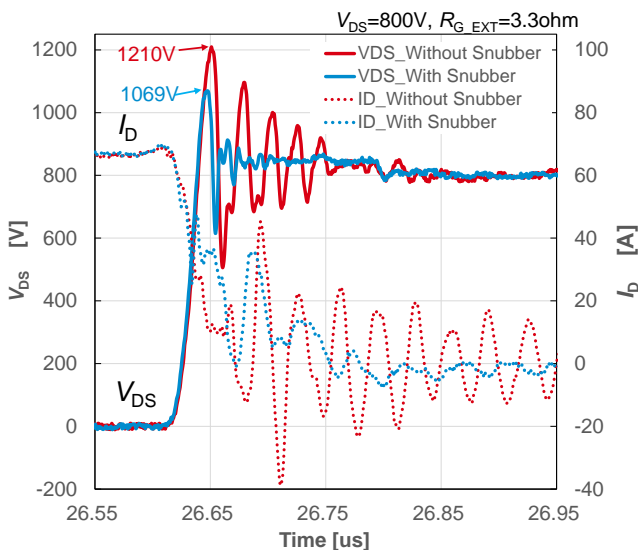
(b) Waveform of V_{DS}, I_D during turn off

Figure 9 turn-off surge comparison（with/without snubber）

The peak voltage using snubber reaches 1069V which is 12% lower when no snubber is used. Without snubber the peak voltage reaches 1210V.

Figure 10 shows the influence of the snubber on the efficiency using a buck converter with the condition of input voltage 400V, output voltage 200V, R_{G_EXT} 6.8Ω and frequency 100 kHz.

Load power was varied from 1kW to 4.8kW. Though snubber made slightly worse efficiency by 0.4% below 4kW range, it improved the efficiency by 0.15% above 4kW range. This is because power loss due to surge voltage increases as load power increases. With the snubber, the surge voltage is suppressed and therefore the switching loss is reduced.
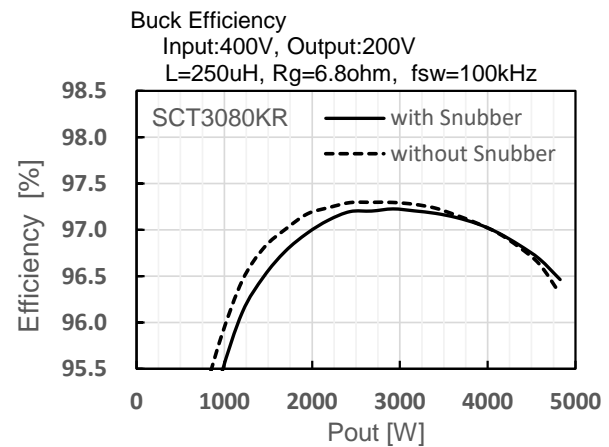

Figure 10 Efficiency comparison of buck converter

Package influence on surge

Package influences on turn-off surge voltage. Figure 11 shows two packages for SiC MOSFET in ROHM. (a) is conventional TO-247N(3L), and (b) is TO-247-4L having driver source pin which is being popular in the market as today.
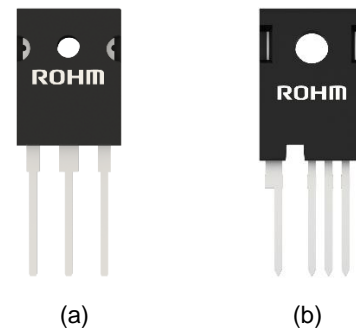

Figure 11 Package example for SiC MOSFET

(a) TO-247N, (b) TO-247-4L

4L type changes route of driving circuit and realizes faster switching than 3L type. Due to the fast switching speed, 4L type tends to have larger surge voltage during turn-on and turn-off compared with conventional 3L. For more details please refer to the application notes "Improvement of switching loss by driver source terminal".

Figure 12 shows wave form comparison of the surge voltage between 3L type and 4L type during the turn-off transient. The test conditions are: $V_{DS} = 800V$, $R_{G\_EXT} = 3.3\Omega$, $I_D = 65A$. The result shows that the 4L type has a higher surge voltage (1210V) than the 3L type (957V).
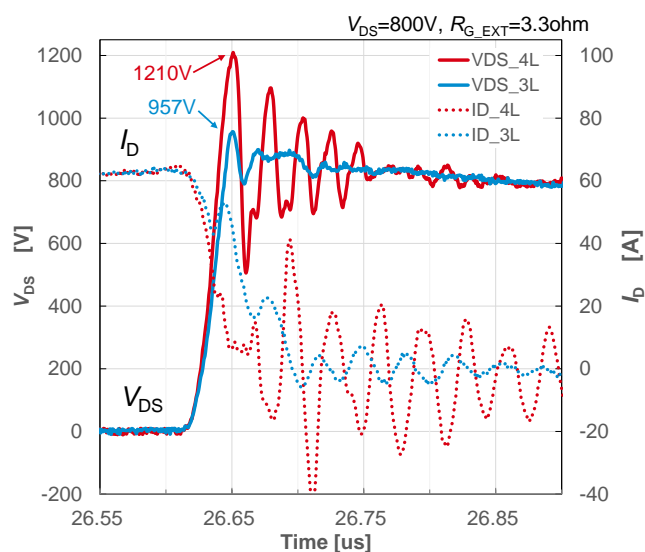
References：

*1 「The Fundamentals of Switching-Mode Converters」
    P95~P107
    K. Harada, T. Ninomiya, W. Gu
    CORONA PUBLISHING CO., LTD., Feb. 1992

*2 「Gate-Source Voltage Surge Suppression Methods」
    Application Note（No. 62AN010ERev.002）
    ROHM Co., Ltd. April 2020

Figure 12 Turn-off surge comparison without snubber
（TO-247N VS. TO-247-4L）

The V_{DS} ringing could cause unexpected surge voltage on the gate-source voltage V_{GS} and exceeds max limitation of V_{GS}. Because the ringing passes not only through $C_{DS,}$ but also through C_{DG} and $C_{GS,}$ as is shown in Figure 7 and Figure 8. ROHM offers countermeasures against the surge in another application note[2] but if the measure is insufficient, snubber circuit should be effective solution.

As described above, gate signal of MOSFETs in bridge topology may influence to each other and may cause unexpected surge voltage. PCB layout should be taken in account to prevent the surge.

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