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Measurement of the Common Source Inductance of Typical Switching Device Packages

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Abstract—The common source inductance is one of the major causes of deterioration of the switching speed and susceptibility of the false triggering for semiconductor switching devices. Practical design of this inductance requires selection of an appropriate semiconductor package because this inductance is greatly dependent on the physical package structure. However, few studies have reported a list of the common source inductance of commercially available packages. In order to list and compare the common source inductance among typical semiconductor packages, this paper carried out measurement of this inductance of actual switching devices mounted on experimental PCBs. This paper employed a recently proposed straightforward measurement technique directly applicable to switching devices mounted on PCBs. As a result, a basic database of the common source inductance of typical packages was presented. The common source inductance was found to be determined mainly by the package type. However, in TO-247 and TO-220 packages, approximately one-third of the total common source inductance was found to possibly vary among the switching devices of the same package due to the dependence on the current rating. Investigation of the physical package structure implied that this dependence was caused by the stray inductance of the bonding wires connecting the semiconductor chip to the source terminal.

Keywords—bonding wire; common source inductance; semiconductor package; stray inductance

I. INTRODUCTION

Recent progress of the semiconductor technology has given rise to the fast switching semiconductor devices. Owing to their fast switching capability, the power converters are often operated at a high switching frequency for effective miniaturization of passive components, such as magnetic devices and capacitors. However, the fast switching may generate significant switching noise on the gate signal, thus deteriorating the switching speed or causing the false triggering of the switching device.

As pointed out in preceding studies [1]–[11], the stray inductance of the source terminal of the semiconductor package is one of the major causes of deterioration of the switching speed and susceptibility of the false triggering. Hereafter, we refer to this inductance as the common source inductance. At the switching, sudden change occurs in the source current. This change induces instantaneous noise voltage across the common source inductance, fluctuating the voltage level of the source on the semiconductor chip. As a result, this noise voltage overlaps with the gate signal. The noise voltage may lower the gate voltage at the switching transition, thus deteriorating the switching speed [1]–[9]. Furthermore, the noise voltage may induce parasitic LC oscillations in the gating circuit [10][11], thus causing the false triggering.

This mechanism suggests that extremely fast switching requires reduction in the common source inductance. Because this inductance is intensely dependent on the structure of the semiconductor package [1][6][11], selecting a switching device in an appropriate package with minimum common source inductance may be essential for designing fast switching power converters. However, manufactures of the switching devices generally provide no data on the stray inductance of the packages including the common source inductance. Moreover, few studies have reported quantitative comparison of this inductance among typical packages.

The reason may lie in the following two difficulties in measuring the common source inductance. Firstly, this inductance is generally too small to be measured conveniently by normal impedance measurement methods using the impedance analyzers or the network analyzers. Secondly, measurement of this inductance generally needs to determine the voltage level of the source on the semiconductor chip, as exemplified in [12], although the semiconductor chip is hidden beneath the mold and direct measurement of this voltage level is not convenient for many electronic engineers.

Certainly, a number of studies utilize the FEM analysis to estimate the common source inductance [2], [8], [13]–[19]. However, the FEM analysis needs detailed knowledge of the internal structure of the semiconductor package, which is generally hidden beneath the mold. Furthermore, measurement based on an experiment should be more preferable than the estimation based on simulation.

To cast a new light on this issue, [20] has recently proposed a promising measurement technique of the common source inductance, as reviewed in the next section. This technique can directly measure the common source inductance without removing the mold of the package. In addition, this technique is directly applicable to a switching device mounted on a PCB.
Besides, this technique is convenient because it needs common instruments for electric engineers. Actually, this technique needs only a sinusoidal signal generator and an oscilloscope.

The purpose of this paper is to list and compare the common source inductance among typical commercially available packages to provide a basic database for practical design of fast switching power converters. Based on this recently proposed measurement technique, this paper measured the common source inductance of actual semiconductor switching devices mounted on experimental PCBs. The next section presents a brief review of this measurement method. Then, section 3 presents the experiment. Finally, section 4 gives the conclusions.

II. MEASUREMENT OF THE COMMON SOURCE INDUCTANCE

Figure 1(a) illustrates the circuit diagram that explains the measurement method employed in this paper. Semiconductor switch S1 is the device under test mounted on a PCB. The drain and source terminals are connected to the signal generator to supply the sinusoidal AC current to the drain. Resistor R and smoothing capacitor C1 are attached on the PCB to connect the gate and source terminals of S1 via the signal generator. Capacitor Cgd is connected to the gate and source terminals of S1 via the signal generator. Voltage 

\[ E_{dc} \]

is applied to the gate of S1, S1 is kept at the on-state. Hence, the drain and source of the semiconductor chip can be regarded as short-circuited. This indicates that \( C_{ds} \) vanishes and \( C_{gd} \) is connected to \( C_{gs} \) in parallel. As a result, we obtain the equivalent circuit of this measurement system as Fig. 2(a).

Because the DC voltage \( E_{dc} \) is applied to the gate of S1, S1 is kept at the on-state. Hence, the drain and source of the semiconductor chip can be regarded as short-circuited. This indicates that \( C_{ds} \) vanishes and \( C_{gd} \) is connected to \( C_{gs} \) in parallel.

The measurement method requires \( C_1 \) and \( R \) to satisfy the following two requirements. One is that \( C_1 \) should have far larger capacitance than \( C_{gs} \). The other is that \( R \) should have sufficiently larger resistance than the impedance of \( C_{gs} \). Therefore, the measurement system as Fig. 2(a).

We can further simplify the equivalent circuit, if we only consider the AC voltage and current in Fig. 2(a). Then, we can approximate that \( L_{gs} + C_{gs} \) and \( C_1 \) are short-circuited, because they are far smaller than \( R \).

As a result, Fig. 2(a) can be further expressed as a simplified equivalent circuit shown in Fig. 2(b).
and the measured current from the signal generator as $V_{ac}$ and $I_{ac}$, respectively:

$$R + j\omega L_s = \frac{V_{ac}}{I_{ac}}(\cos \phi + j \sin \phi),$$  \hspace{1cm} (1)

where $\omega$ is the angular frequency of the AC current, and $\phi$ is the phase difference between the measured voltage and current. Therefore, $L_s$ can be determined as

$$L_s = \frac{V_{ac}}{\omega I_{ac}} \sin \phi.$$ \hspace{1cm} (2)

As we have seen above, this measurement method has the three attractive features. Firstly, this method does not need to remove the mold of the package. Secondly, this method is applicable to a switching device mounted on a PCB. Thirdly, this method can be implemented by a straightforward measurement system with common instruments for electric engineers, such as a signal generator and an oscilloscope.

### III. EXPERIMENT

Experiment was carried out to evaluate the common source inductance of typical semiconductor packages mounted on double-sided PCBs. The tested packages, as well as the experimental semiconductor devices representing these packages, are listed in Table I. Photographs of these packages are shown in Fig. 3. These packages were mounted on experimental PCBs. Specifications of the common source inductance measurement system is presented in Table II.

Figure 4 shows the experimental PCB employed for the measurement of TO-247 package. Because inappropriate layout of a PCB may add common source inductance, as shown later, all of the experimental PCBs were designed to minimize this additional common source inductance. For this purpose, the experimental PCBs satisfied the following three features in the layout pattern:

1. Wire paths $P_d$ and $P_g$ were designed to share no current path on the PCB except for the one point directly connected to the source terminal of the package.
2. Wire paths Pd and Pg were designed to avoid overlap each other.

3. The PCBs were designed to have the ground plane that covers Pd and Pg.

The second and third features are important to avoid undesired magnetic coupling between Pd and Pg.

The magnetic coupling between Pd and Pg is equivalent to the additional common source inductance. Below, we explain the reason based on the equivalent circuit model presented in Fig. 2(a).

The magnetic coupling between Pd and Pg appears as the parasitic transformer. Therefore, the equivalent circuit of the measurement system can be expressed as Fig. 5(a). This parasitic transformer can be equivalently replaced by a T-shaped connection of inductors, resulting in Fig. 5(b). The result indicates that the mutual inductance of Pd and Pg works as the undesired additional common source inductance, which should be minimized for evaluation of the common source inductance contributed by the packages.

Table I lists the measurement results of the common source inductance; and Fig. 6 presents comparison among typical packages. The horizontal axis in Fig. 6 is the DC current rating of the switching devices to investigate the dependence on the current rating.

Figure 6(a) shows the result of the through-hole packages. The common source inductance ranged from 3nH to 8nH. This inductance was found to be dominantly determined by the package type. Smaller package such as I-PAK showed less common source inductance as is naturally supposed. However, TO-247 and TO-220 packages showed comparatively large variety among the devices of the same package. Actually, one-third of the total common source inductance was found to vary due to the dependence on the current rating.

As for the surface mount packages, the common source inductance ranged from 1nH to 6nH. This inductance was also found to be dominantly determined by the package type. However, no apparent dependence on the current rating was found in the surface mount packages.

To summarize, the common source inductance was found to be mainly determined by the package types. However, TO-247 and TO-220 packages further showed additional dependence on the current rating. In the next section, the reason of this
dependence is investigated by analyzing the physical structure of the package beneath the mold.

IV. DEPENDENCE ON THE CURRENT RATING

This section investigates the physical package structure beneath the mold to elucidate the reason of the dependence on the current rating among the switching devices of TO-247 and TO-220 packages. Generally, a semiconductor chip is directly mounted on a base plate, which forms the drain terminal. Therefore, the stray inductance of the drain terminal may have little variety among the switching devices of the same package. On the other hand, the semiconductor chip is connected to the source terminal through the thin bonding wires. Particularly, the bonding wires tend to have large variety in the diameter, the length, and the number. As a result, the common source inductance may have comparatively large variety among the switching devices even of the same package. Therefore, we investigated the dependence of the common source inductance on the bonding wires.

No data on the bonding wires generally appear in the datasheets provided by the manufacturers of the switching devices. Therefore, we observed the bonding wires hidden beneath the mold to remove the mold mechanically using a handy grinder. Then, we measured the diameter, the length, and the number of the bonding wires that connect the semiconductor chip to the source terminal. The results is summarized in Table I. (As for SOT-223 and SOT-23, we failed to expose the bonding wires because of too small package size. Therefore, no parameters of the bonding wires were obtained for these packages.)

According to the electromagnetism, a round thin wire with the diameter $r$ and the length $l$ has the stray inductance $L_{\text{wire}}$ expressed as

$$L_{\text{wire}} = \frac{\mu_0 l}{2\pi} \left( \ln \frac{4l}{r} - \frac{3}{4} \right),$$

(3)

where $\mu_0$ is the permeability of the vacuum. Therefore, we can estimate the common source inductance contributed by the wire bonding $L_{bwire}$ as

$$L_{bwire} = \frac{\mu_0 l}{2\pi N} \left( \ln \frac{4l}{r} - \frac{3}{4} \right),$$

(4)

where $N$ is the number of the bonding wires connected in parallel. We calculated $L_{bwire}$ based on (4); and compared the result with the common source inductance measured in section III as well as the current rating of the switching devices. However, SOT-223 and SOT-23 are omitted from the comparison because no data of the bonding wires were obtained. In addition, I-PAK and D2-PAK are also omitted because difference in $L_{\text{wire}}$ was
found to be too subtle among the tested devices to discuss the dependence.

Figure 7 shows the comparison result with the measured common source inductance. As can be seen in the figure, the stray inductance of the bonding wires was found to have close correlation with the common source inductance in TO-247 and TO-220 packages. The similar relation was also found in D-PAK package, although the correlation was weak.

Figure 8 shows the comparison result with the current rating. The result revealed that stray inductance of the bonding wires have comparatively good correlation with the current rating in TO-247 and TO-220 packages, whereas no apparent correlation was found in D-PAK package. This result implies that the bonding wires is the main reason of the dependence of the common source inductance on the current rating in TO-247 and TO-220 packages.

V. CONCLUSIONS

The common source inductance is one of the major causes of deterioration for the switching speed and susceptibility of the false triggering of semiconductor switching devices. Therefore, reducing the common source inductance is intensely required for fast switching. Selecting an appropriate semiconductor package with minimum common source inductance may be essential for designing fast switching power converters because the physical structure of the package significantly contributes to the common source inductance.

In order to list and compare the common source inductance of typical commercially available packages, this paper carried out measurement of this inductance in actual switching devices mounted on PCBs. As a result, a basic database of the common source inductance of typical packages was presented. The common source inductance was found to have dominant dependence on the package type. In addition, dependence on the current rating was found in TO-247 and TO-220 packages. Investigation of the physical package structure implied that this dependence is caused by the stray inductance of the bonding wires, which tends to have correlation with the current rating.

REFERENCES