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Research Article

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MOSFET'S 1/f Noise's Equivalent Capacity Model and the Switching Time Analysis

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Abstract

Aimed at the influence of the 1/f noise on the switching time of N-MOSFET, this article puts forward an equivalent capacity model of the 1/f noise. Based on this model, the paper tries to present a qualitative analysis of the effect exerted by 1/f noise to the switching time of MOSFET. Furthermore, the relationship between this capacitance and frequency exponent of 1/f noise was analysed. Finally, CoolMOS^{TM} Power Transistor IPW60R045CP produced by Infineon is used to verify the analysis results and prove that the driving pulse frequency higher, the influence of 1/f noise on the switching time is weaker.

Keywords: MOSFET switching time, 1/f noise, equivalent capacity model

1. Introduction

The current research on MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor) switching speed mostly focus on MOSFET external factors such as the choice of driving resistance, PCB（Printed Circuit Board）layout, etc., but less involve MOSFET internal factor such as the junction capacitance. As MOSFET is widely used in different fields, its switching characteristics are also different: Miller effect cannot be ignored in high frequency circuits and 1/f noise may also have great effect on its switching speed in low frequency circuits[1]. The loss of Power MOSFET is parallel to its switching time when it is used in low frequency and high power occasions. In the design of low switching loss circuits, it is necessary to analyze any factors which have influence on the switching speed of MOSFET. As there is no final conclusion about the theory of 1/f noise in MOSFET now, the analysis of the MOSFET noise mainly focus on its thermal noise, and there were few theories that had been put up about 1/f noise on the influence of the MOSFET switching time. On the basis of the fundamental research of the current 1/f noise, this paper proposes a new kind of 1/f noise equivalent capacitance model with the example of enhanced MOSFET, which is applied to the study of 1/f noise on the influence of the MOSFET switching speed.

2. MOSFET equivalent circuit model and its switching time analysis

The N-channel MOSFET equivalent circuit model is shown in Fig.1. As Jess Brown described in[2],when the parasitic components of a practical circuit are ignored, the turn-on time periods of a MOSFET can be illustrated by formulas(1)-(3).The current and voltage of turn-on transient is shown in fig.2.

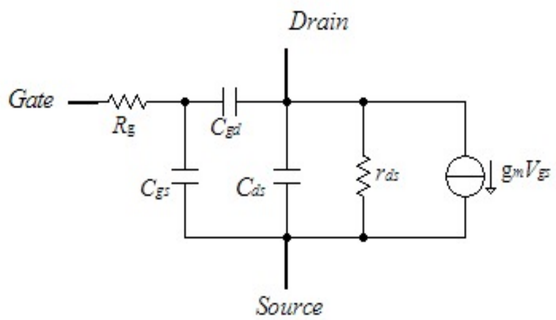

Fig. 1. N-MOSFET equivalent circuit model

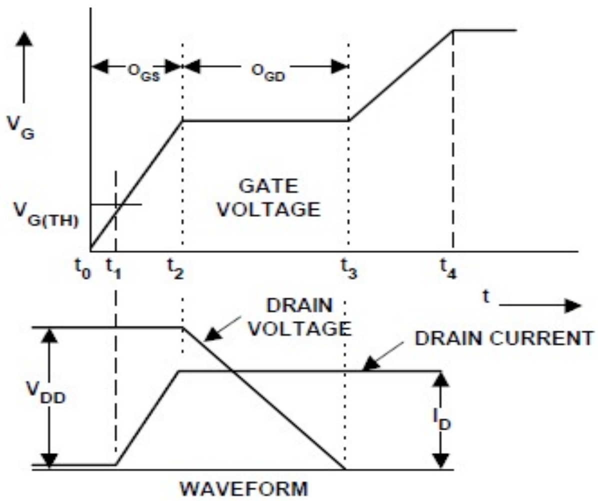

Fig.2. Turn-on transient of MOSFET

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$$t_1 = (R_g + R_i)(C_{gs} + C_{gd}) \ln\left(\frac{1}{1 - \frac{V_{GS(th)}}{V_{GS\_t}}}\right) \quad (1)$$

$$t_2 = (R_g + R_i)(C_{gs} + C_{gd}) \ln\left(\frac{1}{1 - \frac{V_{gp}}{V_{GS\_t}}}\right) \quad (2)$$

$$t_3 = \frac{(V_{DS\_off} - V_f)(R_g + R_i)C_{gd}}{V_{GS\_t} - V_{gp}} \quad (3)$$

Where

R_g : internal gate resistance
R_i : external gate resistance
$V_{GS(th)}$: the gate threshold voltage of the MOSFET V_{gp}:the miller-plateau voltage
V_{GS_t}: the target voltage of V_{GS}
V_f : the voltage across the MOSFET when conducting full load current
V_{DS_off} : the initial voltage of V_{DS} prior to discharge

During the period of t_0 to t_1, the gate driver voltage is gradually rising with the charging of C_{gs} till it reaches $V_{GS(th)}$. At this time, V_{ds} begin to drop gradually. During the whole period of t_0 to t_2, the current from the gate driver is charging C_{gs} and discharging C_{gd}. At the time of t_2, V_{GS} reaches a value of V_{gp}, V_{ds} begin to drop sharply. During the time t_2 to t_3, as V_{ds} drops from a supply voltage to zero and C_{gd} is discharged from the supply voltage to $-V_{gp}$, almost all of the current from the gate driver flows through to provide this energy. At the time of t_3, V_{ds} reaches nearly zero, and the gate driver current would charge C_{gs} again until V_{GS} reaches the gate driver voltage[3].

In this paper mainly focus on the internal factor of MOSFET which would have impact on its switching speed, the analysis of external factors is ignored.

3. Remodelling of MOSFET with the equivalent capacity model of the 1/f noise

Obviously the switching time of MOSFET is strongly associated with its junction capacity. The drain PN junction of the MOSFET is under reverse bias when it works, and the current flows through the PN junction is almost the very weak reverse saturation current. On the other hand, as the gate and the channel are insulated, the gate current is also extremely small. So, the shot noise of gate can be ignored. The noise in MOSFET is mainly 1/f noise and thermal noise, and 1/f noise would be the main noise when the frequency is under 20k. The 1/f noise in MOSFET is produced in its gate, and its turn-on and turn-off is controlled by the gate voltage, so, the 1/f noise must be have impact on the switching speed of MOSFET [4].

There is no final conclusion about the characterization method of 1/f noise, most of its research and description is based on its power spectral density (PSD). It is now widely accepted that the PSD of 1/f noise is given by

$$S(f) = \frac{K}{f^M} \quad (4)$$

Where

K : 1/f noise coefficient
M : 1/f noise frequency index

With the rising of frequency, the PSD of 1/f noise is dropping and the higher the frequency the bigger the value of M [5],[6]. In fact, because of its certain randomicity, the PSD of 1/f noise is not constant under a certain frequency. Therefore, 1/f noise is strongly bound up with frequency; its PSD is inversely proportional to its frequency index. As mentioned in [7], in switched MOSFET circuits, 1/f noise is more sensitive and it would be inaccurate using the standard 1/f noise model to analysis these circuits.

Based on the above discuss, the model that 1/f noise have impact on MOSFET switching speed is equivalent to a variable capacity model which is related to the frequency. Therefore, when the effect of 1/f noise is taken into account, the N-channel MOSFET equivalent circuit model is shown in Fig.3, and the switching time law is (5).

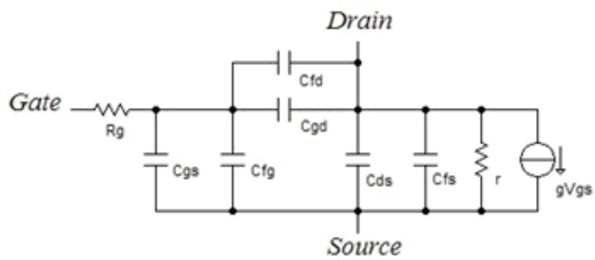

Fig.3. N-MOSFET equivalent circuit model with 1/f noise equivalent capacity model

$$t'_1 = (R_g + R_i)(C_{gs} + C_{gd} + C_{fg}) \ln\left(\frac{1}{1 - \frac{V_{gp}}{V_{GS\_t}}}\right) \quad (5)$$

Where

C_{fg} : The value of the equivalent capacity

Thus, taken this equivalent capacity into account, the influence of 1/f noise on switching speed can be directly incoming the formula of calculating the MOSFET switching time in the form of equivalent capacitance, so as to calculate and analyze the switching time. According to the relationship between gate capacity and PSD of 1/f noise and frequency [8],[9], the value of the equivalent capacity can be derived as formula (6).

$$C_{fg} \propto f^{1-M} \quad (6)$$

4. MOSFET switching time test under different frequencies

In order to verify the rationality of the equivalent capacity model, it is necessary to test the MOSFET switching time under low frequency. The terminal noise can be ignored under low frequency according the previous analysis and the different of switching time under different frequency can be considered primarily the influence by 1/f noise. The circuit is shown in Fig.4 is used to measure the switching time of MOSFET.

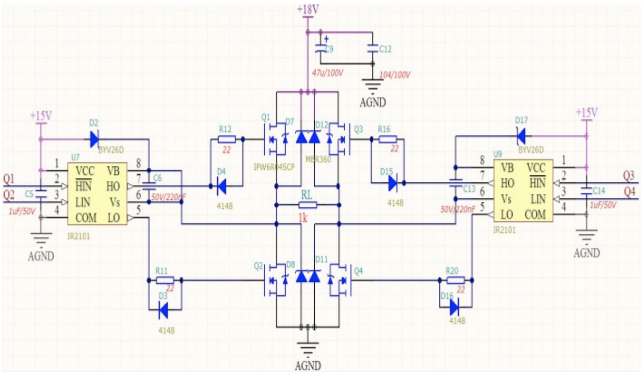

Fig.4 MOSFET switching time test circuit

It is a full bridge inverter circuit which is commonly used. The power transistor is CoolMOS^{TM} Power Transistor IPW60R045CP which is produced by Infineon. The load of this circuit is a resister of 1kΩ, and its influence on the switching time won't make a deep analysis in this paper. The MOSFET switching time under different frequency is tested in the experiment and table1 shows the test results. The test equipment is Agilent Technologies Digital Storage Oscilloscope 5032A.

Table1:MOSFET turn-on time under different driving pulse frequencies

Frequency (Hz)	138	284	580	820	1050	1430
Turn-on time(ns)	94	88	85	80	75	70

Fig.5 and fig.6 shows the Q4 drain voltage transient waveform under the driving pulse frequency of 580Hz and 1050Hz.

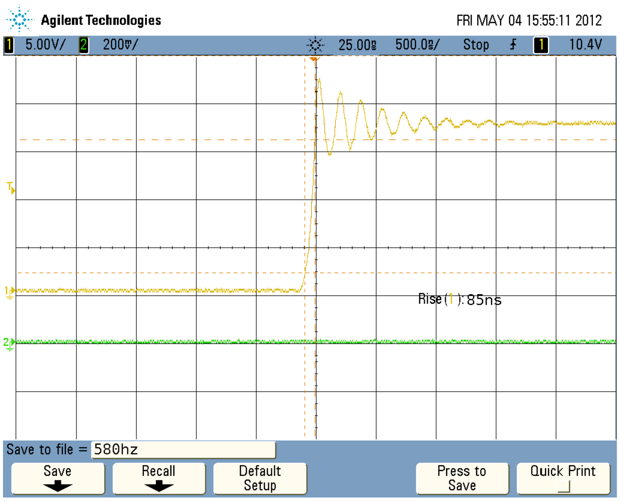

Fig.5. turn-on transient waveform of drain voltage under 580Hz

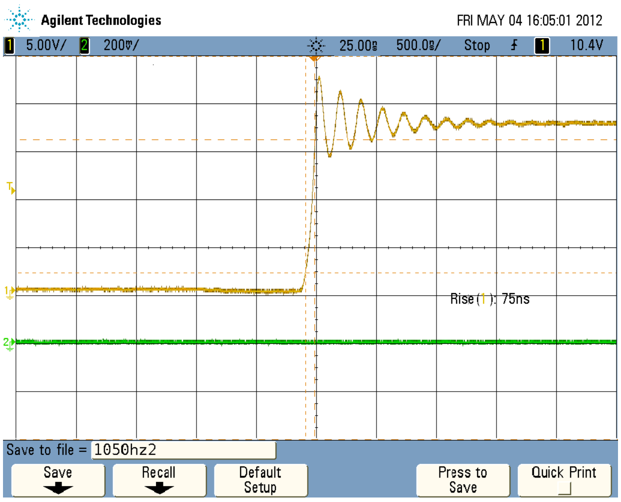

Fig.6. turn-on transient waveform of drain voltage under 1050Hz

The experimental results showed that with the rising of driving pulse frequency MOSFTE switching time is decreasing. So, the driving pulse frequency is higher, the influence of 1/f noise on the switching time is weaker, and the variation of the equivalent capacity is more obvious under low frequency. Moreover, with the rising of driving pulse frequency, the PSD of 1/f noise is decreasing and its frequency index is increasing, then the equivalent capacity would be too small so that it can be ignored. At this time, the MOSFET switching time is mainly depend on the input capacity.

5. Conclusion

Based on the depth analysis of MOSFET switching time, this article put forward a model of 1/f noise--- equivalent capacity model, which is aimed at the influence of 1/f noise on switching speed under low switching frequency. Moreover the relationship between the value of equivalent capacity and switching frequency and 1/f noise frequency index is given. By using the equivalent capacity model, we have done the theoretical analysis and test for MOSFET switching time under different frequency of driving pulse. From the experimental results, it can be seen that the MOSFET switching time is decreasing with the frequency of driving pulse rising. Therefore, it has a certain practical significance to analyze the MOSFET switching time by using the equivalent capacity model. And some further research would be needed to make this equivalent capacity model more concrete and practical.

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