A RADIO-FREQUENCY MOSFET DRIVER

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Abstract: High power MOSFETS have become synonymous with power electronics applications. The ability of high power MOSFETS to act as a switch makes it the ideal switching device, where maximum voltage and zero current must occur when the device is open. When closed, the MOSFET must allow maximum current to flow with zero voltage across it [1][2][3]. This technique of switching between maximum and zero voltage across the high power MOSFET is readily achieved at frequencies below 1 MHz. Raising the frequency to within the radio-frequency range presents numerous challenges, as high power MOSFETS tend to have a frequency cut-off point. This paper attempts to address the switching habits and limits of high power MOSFETS within the radio-frequency range by means of computer simulation and experimental verification.

Key words: MOSFET, radio-frequency

1. INTRODUCTION

The advantages of utilizing high power MOSFETS in switching applications are numerous, some of which are illustrated in Table 1 [4][5]. It is mainly due to these benefits that high power MOSFETS must in some or other way be incorporated into radio-frequency applications. What factors though limit the operating frequency of high power MOSFETS? How can these MOS circuits be effectively driven so as to attain their maximum operating frequency? Finally, is there a similarity between the experimental and simulated results of the radio-frequency MOSFET driver?

Table 1: Advantages of high power MOSFETS

<table>
<thead>
<tr>
<th>Features</th>
<th>Benefits</th>
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<tr>
<td>No minority carriers</td>
<td>High gate input resistance</td>
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<tr>
<td></td>
<td>Very high gain</td>
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<td></td>
<td>Very high switching speeds</td>
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<td></td>
<td>Nearly unlimited fan-out</td>
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<td>Thermally degenerate</td>
<td>No current hogging</td>
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<td></td>
<td>Accepts high inrush drain current</td>
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<td>Improved safe operating area</td>
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</table>

It has already been noted in the past that the speed limitations of MOS circuits is due entirely to circuit capacitances and the inability of the MOSFET to charge and discharge these capacitances [6][7][8][9]. Intrinsic cut-off frequencies of MOS devices themselves are in the order of 1 GHz. It could thus be said that MOSFETS are not really inherently bound to frequency limitations within the radio-frequency range, because of the absence of minority carrier transport. High frequency operation is though limited by the transient time across the drift region and the rate of charging of the input gate capacitance. The transit time limited frequency response is a function of breakdown voltage [10]:

\[
 f_T = \frac{6.11 \times 10^{11}}{(1 + \frac{L}{d}) \times BV_{pp}^{1.167}} \text{ Hertz} \quad (1)
\]

Where:

\[ L = \text{channel length in micrometers} \]
\[ d = \text{drift region thickness in micrometers} \]
\[ BV_{pp} = \text{Breakdown Voltage} \]

The input gate control charge can be expressed as [11]:

\[
 Q_{gate} = C_{iss} \times V_g \text{ Coulomb} \quad (2)
\]

Where:

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The input capacitance, in pico farad, being the sum of \( C_{GS} \) (the gate to source capacitance) and \( C_{DG} \) (the drain to gate capacitance).

\[ V_{gs} \] gate to source voltage

The power required then to drive the gate of the MOSFET is given by [11]:

\[
P_{\text{Gate}} = 0.5 \times C_{iss} \times V_{gs}^2 \times f \quad \text{Watts} \tag{3}
\]

Where:

\[ f = \text{input frequency in Hertz} \]

The high power MOSFET is in reality a bulk semiconductor, where a gate potential controls the majority-carrier current [4]. The fundamental issue is thus to pump charge into the gate of the MOSFET and then to quickly withdraw it again. This must occur at a rate of a few nanoseconds and at a gate voltage of between 0 and 10 V, so as to enable the MOSFET device to operate correctly within the radio-frequency range [12]. The maximum input gate voltage must not exceed 15 V [13]. It has been documented that high power MOSFETs can achieve switching speeds of 100 ns or less when driven from a gate drive circuit with a low output impedance, being able to sink and source relatively large currents [13]. The complementary emitter follower is an example of such a gate drive circuit. More recently though, a practical gate drive circuit was designed and built in conjunction with a frequency synthesizer operating between 100 kHz and 8 MHz. This gate drive circuit utilized a complementary emitter follower and proved very successful in driving the gate of a high power MOSFET [14].

3. COMPLEMENTARY EMITTER FOLLOWER

Operating a high power MOSFET as a switch requires a change between the lowest and highest resistance states of the device in the shortest possible time. Ultimately the switching performance of the MOSFET is determined by how quickly the voltages can be changed across the gate input capacitances, which are the sum of the gate to source capacitance and the drain to gate capacitance [11] [8]. It may be shown that this can be done with a complementary emitter follower, an example of which is sketched in Figure 1. If positively pulsed, VCC is directly coupled to the gate via T1 with hardly any series resistance. When the pulse is zero, T2 conducts and shorts the gate of the MOSFET to ground with again virtually zero resistance.

Two further noteworthy properties of the complementary emitter follower is firstly that the two base-emitter junctions protect each other against reverse breakdown and secondly it does not require any Schottky diode for reverse current protection [15].
However, the required gate drive power increases to 1 W when an IRFP250 MOSFET with a $C_{iss}$ of 2159 pF is utilized in the circuit [17]. For this reason a second complementary emitter stage was included to handle higher amounts of power dissipation required by MOSFETS with higher input gate capacitances. The minimum $f_T$ of both the TIP31C and TIP32C are specified to be 3 MHz according to their respective data sheets [16].

4. SIMULATION MODEL

The SPICE model for the IRF610 high power MOSFET was initially incorporated into the SIMETRIX simulation software package. Figure 2 shows the circuit layout of the MOSFET driver compiled within the simulation package.

The supply voltage was initially set to 15 V. The input signal to the first complementary emitter stage was a 7 MHz 12 V peak square wave. A 50% duty cycle was utilized with the total time period being 143 ns. $R_2$ was included to prevent the gate of the high power MOSFET from ever floating, which could be detrimental to the MOSFET device if under full load conditions. The 1.5 $\mu$H coil was included in the experimental model as too much ringing was observed on the digital oscilloscope display. The load resistance was varied between 50 $\Omega$ and 75 $\Omega$, and yet did not alter the performance of the radio-frequency MOSFET driver. Voltage probes were included at the output of the second complementary emitter follower as well as across the high power MOSFET to ground.

5. RESULTS

5.1 Simulated results

Figure 3 shows the time domain signal as obtained from the simulated model. The smaller amplitude signal, $A$, represents the output of the complementary emitter follower which is connected via the 1.5 $\mu$H coil to the gate of the high power MOSFET. The larger amplitude signal, $B$, is the output from the high power MOSFET. The time period can be seen to be 143 ns that equates to an operating frequency of 7 MHz. The duty cycle is found to be less than 50%. The input signal voltage is also discernable at 11.87 V, while the output across the MOSFET swings from 0 V to 16 V, which is roughly the supply voltage.

5.2 Experimental results

The output frequency spectrum of the experimental model is illustrated in Figure 4 while Figure 5 shows the time domain signal of the experimental model as obtained form a TEKTRONIX digital oscilloscope.

![Figure 4: The output frequency spectrum of the experimental model](image)

![Figure 5: The input and output signal of the high power MOSFET as obtained from the experimental model](image)
CH1, in Figure 5, represents the output signal from the complementary emitter follower, which is connected to the gate of the high power MOSFET. CH2 illustrates the output taken from across the MOSFET to ground. Note the time period for the output signal, CH2, as being 143 ns while its voltage is set at just less than 20 V. The input signals voltage, CH1, is less than 15 V.

Figure 6 illustrates a significant similarity between two output signals of the complementary emitter follower when under load and when isolated from the load. A comparison was also made between the output waveforms of the simulation model and the experimental model which is illustrated in Figure 7.

Figure 6: The output signal from the complementary emitter follower for the following two conditions; X - isolated from the gate of the high power MOSFET and; Y - connected to the gate of the high power MOSFET.

The X signal in Figure 6 represents the output of the complementary emitter follower when isolated from the gate of the high power MOSFET, while the Y signal is the output of the complementary emitter follower when connected to the MOSFET's gate. Two notable differences are discernable upon closer examination. The Y signal has a wider falling trail and a somewhat more curved ground voltage than the X signal has.

A comparison between the outputs of the two models, as shown in Figure 7, also reveals some significant differences. The experimental model shows a rise time of around 25 ns compared to the 20 ns of the simulated model. Similarly, fall times for the experimental model are found to be 25 ns while the simulated model is around 15 ns. The experimental model has a flatter supply voltage response than that of the simulated model. On the other hand, the simulated model's ground response is better than that of the experimental model.

6. FUTURE WORK

Experimental tests must still be carried out on the usefulness of the IRF530 in the radio-frequency range. It has the ability to source a larger amount of current and dissipate more power than the IRF610 does. It does though have a larger input gate capacitance than the IRF610 and this could cause significant changes in the performance of the high power MOSFET driver.

Another line of thought in driving high power MOSFETS encompasses the idea of using a negative and positive gate bias voltage. Pumping charge into and out of the gate of high power MOSFETS could thus result in faster switching times.

High speed MOSFET driver IC's, such as the DEIC420, are also commercially available that enable the switching of high power MOSFETS up to around 45 MHz [18]. These packages have the disadvantage of not being as cost-effective as the two stage complementary emitter follower presented here. However, a correlation between the complementary emitter follower and MOSFET driver IC may reveal certain similarities or differences.

7. CONCLUSION

From the above results, and in particular Figure 7, it is clear that the experimental model and the simulated model's results agree significantly. Furthermore, the ability of the high power MOSFET to operate at a radio-frequency of 7 MHz has been shown. Although the output from the MOSFET does not exactly resemble the input square waveform, it does exhibit the quality of being able to switch rapidly between ground and VCC voltage levels. Figure 6 furthermore confirms that the high power MOSFET gate does not significantly alter the output waveform of the complementary emitter follower.

The gate power required to switch high power MOSFETS...
on and off is primarily influenced by the frequency of operation, gate voltage and input gate capacitance. The complementary emitter follower is capable of operating within the radio-frequency range of 7 MHz and of supplying the necessary gate voltage of between 10 and 15 V. It also has the ability to source and sink large currents required to rapidly charge and discharge the input gate capacitances. Both the experimental and simulated results thus confirm that the complementary emitter follower is indeed a worthy radio-frequency MOSFET driver.

8. REFERENCES