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Article

Research on Switching Characteristics Based on Optimization Design of SiC MOSFET Drive Circuit

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Abstract: With the increasing emphasis on energy conservation, emission reduction and environmental protection, the application prospect of SiC power devices is becoming more and more broad. In the high frequency application of SiC MOSFET, the change rate of voltage and current in the turn-on and turn-off process increases with the increase of switching frequency. Also, the current and voltage spike oscillation phenomenon is gradually intensified due to the influence of circuit stray parameters. Based on the analysis of SiC MOSFET characteristics, the paper discusses the design requirements and design principles of SiC MOSFET drive circuit. Then, taking the SiC module C2M0080120D of Cree Company as an example, a driver circuit design is realized through the ACPL-355JC optocoupler driver module of Broadcom Company. The circuit not only has the characteristics of fast transmission delay and excellent performance, but also has the functions of overload and short circuit protection. The driving circuit is verified by LTspice simulation software, and the switching characteristics of SiC MOSFET under different working conditions are studied in depth. The experimental results show that the driving circuit can improve the switching time of SiC MOSFET and effectively solve the problem of current and voltage spike oscillation, which lays a foundation for the practical application of SiC MOSFET in the future.

Keywords: SiC MOSFET; switching characteristic; drive circuit; LTspice

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1 Introduction

The core of power electronics technology is power devices, which play a key role in the development trend of high frequency and high power density[1-3]. As a new type of semiconductor material, SiC power devices show great potential in high temperature, high power and high voltage applications which are used in electric vehicles, solar inverters, industrial power and other fields due to their great physical properties such as low conduction losses, high switching speed, high breakdown voltage and low drift region resistance[4,5]. SiC power devices deliver higher power densities, lower switching losses and higher operating temperatures than traditional silicon power parts, which makes them an ideal choice for realizing high-efficiency energy conversion and high-performance power electronics systems[6,7].

In recent years, more and more semiconductor firms have launched commercialized SiC MOSFETs, and many researchers have done many studies on the application design of SiC devices, among which the design of SiC MOSFET switching characteristics and driving circuits has become popular research direction[8].

In reference[9], a driving circuit that is suitable for SiC MOSFET is designed. The output pulse width of the circuit is continuously adjustable. The circuit has good stability and can work reliably for a long time, but the response time between the input and output signals of the driving circuit is long[9]. An improved active drive circuit is designed in reference[10] to verify the basic driving characteristics and which is effective to suppress voltage and current spikes, frequency oscillations and crosstalk problems[10]. In references[11-15], a driving circuit suitable for medium and high-power applications and high-speed switches is designed, which adopts a gate active clamping circuit with negative voltage turn-off. It not only solves the problem of peak oscillation caused by fast switching speed, but also has good suppression of overshoot of V_{ds} to ensure the stability of gate voltage. However, the circuit parameters are complicated to design[11-15]. Reference[16] designs a driving circuit for SiC MOSFET to slow down the switching speed by paralleling capacitors at the gate and source ends of the device. The driving problem caused by the crosstalk of the bridge arm is avoided at the expense of efficiency[16]. Reference[17] proposes a short-circuit protection design method that can be directly integrated into the traditional SiC power semiconductor drivers, and experimentally analyzes the traditional structure of the totem pole. On this basis, a BJT+MOSFET power amplifier circuit is designed, which is better than the traditional structure in terms of stability[17]. On the basis of summarizing the requirements of SiC MOSFET drive circuit, reference[18] designs the optocoupler-isolated drive circuit and the pulse transformer-isolated drive circuit. Both drive circuits have fast switching rates[18]. In this paper, we will realize a driving circuit design with the help of the ACPL-355JC optocoupler driving module of Broadcom, and use the double-pulse test platform to investigate the voltage peak oscillation issue existing in the switching process of SiC MOSFET. Besides, the driving circuit is verified using LTspice simulation software, and the effects of the switching characteristics of SiC MOSFETs under different operating conditions are discussed.

Table 1 Comparison of semiconductor material features

Material	Si	GaAs	GaN	SiC
Energy bandgap (eV)	1.1	1.4	3.4	3.3
Electron mobility (cm^2/Vs)	1350	8500	2000	1000
Critical electric field (kV/cm)	0.3	0.4	3.3	2.8
Electron drift velocity (10^7cm/s)	1	1	2.7	2.2
Thermal conductivity (W/cm·K)	1.5	0.5	1.3	4.9

2 Dynamic characteristics analysis of SiC MOSFET

The dynamic characteristics of SiC MOSFET can be analyzed by measuring the key parameters in the switching process. A double-pulse test simulation circuit is built based on the LTspcie simulation software, where the upper and lower tubes each have a SiC MOSFET device, in which the lower tube is used as a test tube. Besides, a double-pulse voltage is applied to the gate source pole of the lower tube, and the lower tube is used to control the circuit switching. Since the inductor current cannot be changed abruptly, the inductor current will continue to flow through the upper tube when the lower tube is closed. Thus, the upper tube is equivalent to a fast recovery current-continuing diode, which plays a freewheeling role. Hence, during the simulation process, a negative voltage is applied across the gate-source terminals of the upper tube so that the upper tube is turned off when the test tube is operating. The simulation circuit diagram shows that the switch is turned on at T1, and the inductance current rises linearly. The switch is turned off at T2, and the current flows through the upper tube. The switch is turned on at T3, and the upper tube recovers reversely. The drain-source voltage is 0V when the switch is on, and the power supply voltage is 800V when the switch is off.

This paper analyzes the performance characteristics of the lower tube at the first turn-off moment and the second turn-on moment for the SiC MOSFET half- bridge module[19]. Under the condition of 800V DC bus voltage and 30A freewheeling inductor current, the dynamic characteristics of SiC MOSFET are tested. The switching waveforms are obtained as shown in Fig.1. From the graph, it can be observed that there is significant

Table 2 Double pulse circuit simulation parameters

Parameter	Input Voltage VDC (V)	Load Current I_D (A)	Load Inductance L_{load} (μH)	Driver Resistors R (Ω)
Value	800	30	160	5

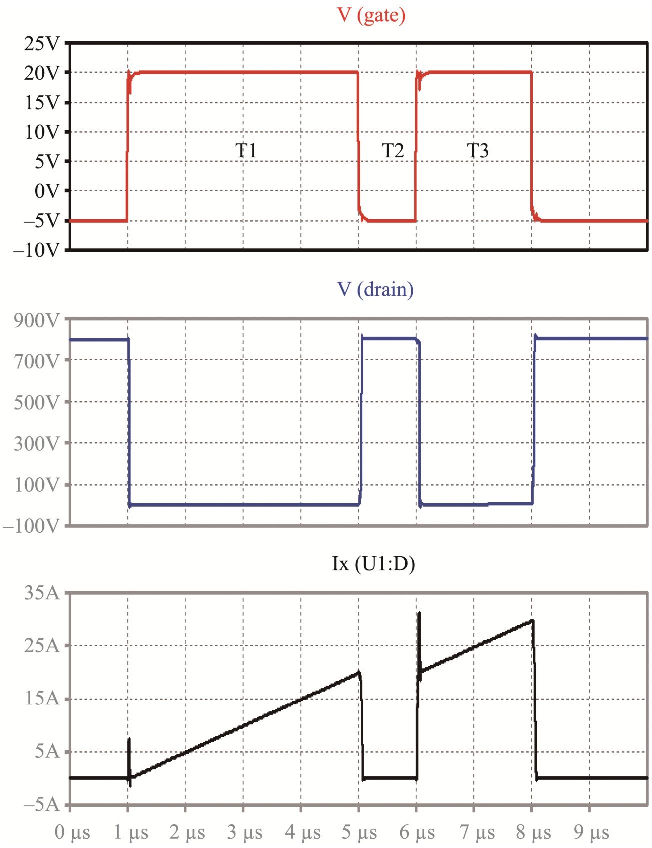


Fig.1 Double-pulse switching simulation test waveforms

oscillation in the gate voltage during the turn- on process, and the rise time of the drain-source voltage is 19ns, while the fall time is 13ns.

3 SiC MOSFET driver circuit optimization design

3.1 Basic requirements for driver circuit design

As SiC MOSFET research continues to mature, there is an increasing demand for frequency and voltage performance in power devices. Therefore, the driver circuit design is important in enhancing the operating performance of SiC MOSFET devices. In contrast to Si MOSFET, the design of SiC MOSFET driver circuits is to be considered:

(1) The drive circuit is an important link between the control and main circuits, and must be considered electrically isolated;

(2) The driver circuit should satisfy the high peak drive current demand of the SiC MOSFET to overcome the Miller effect;

(3) A suitable drive resistance is selected for the drive circuit to control the switching loss of the SiC MOSFET;

(4) The driver circuit adopts negative voltage shutdown technology, which effectively prevents the phenomenon of mistaken conduction, and improves the anti-interference performance of the circuit at the same time;

(5) When a short-circuit or overload fault occurs, the drive circuit needs a corresponding protection circuit to make it work reliably.

3.2 Driver circuit design principle

The driving circuit is essentially the process of charging and discharging the input capacitance of the power device. It is necessary to provide sufficient driving current to ensure the fast charging and discharging of the input capacitance to maintain the efficient switching operation of the power device. The drive voltage and current should be considered first when designing the drive circuit. According to the SiC MOSFET model datasheet, in order to ensure the switching speed and prevent the V_{GS} from being broken down, the gate turn-on voltage is selected to be +20V and the turn-off voltage is -5V. Insufficient driving current will lead to a slower switching speed and longer response time of the device, which increases switching loss.

The average driving current required is calculated according to the following formula :

$$I_g = \frac{Q_C}{t_{d(on)} + t_r}$$

Where $t_{d(on)}$ represents turn-on delay time .

t_r is rise time.

Q_c is the total gate charge.

According to the parameters of the data manual, the average driving current required during the opening process is 1.92 A. The schematic diagram of the drive circuit is shown in Fig.2. The SiC MOSFET driver chip uses the ACPL-355JC, which is a fast transmission delay, with such functions as overload and short-circuit protection. The peak drive current of 10A fully meets the drive requirements.

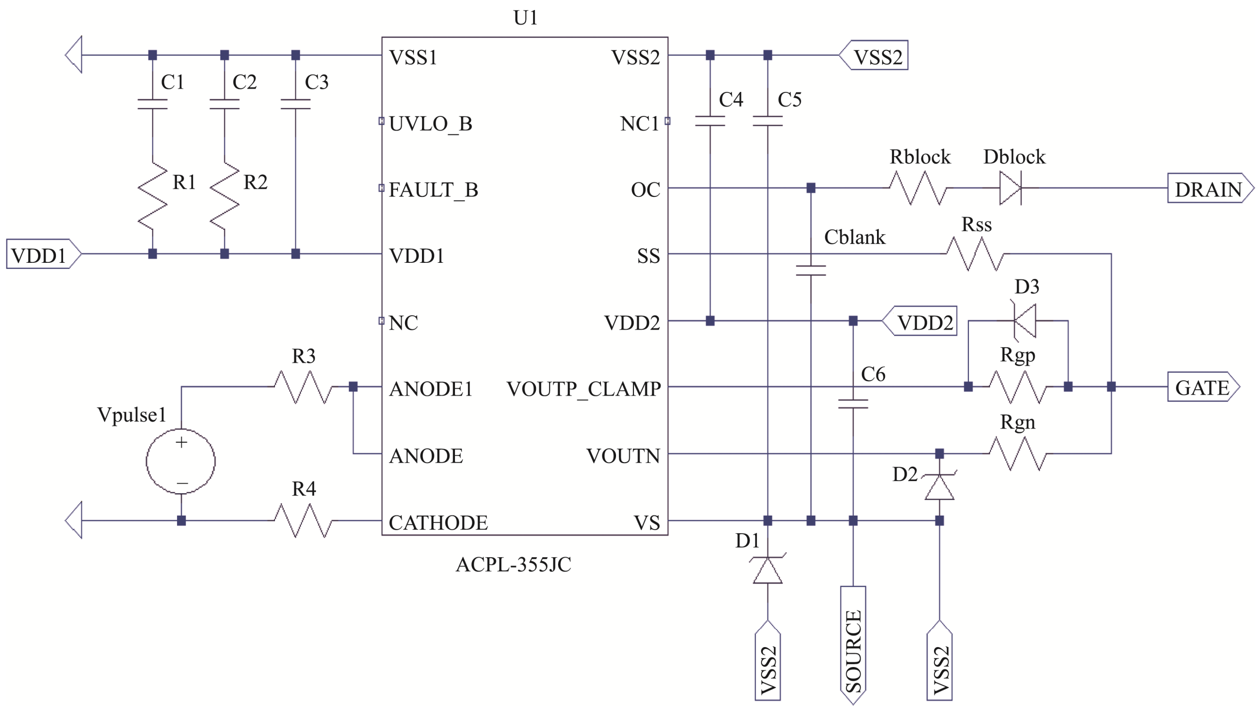


Fig.2 Driver circuit schematic

4 Double pulse testing circuit simulation

The dynamic characteristics of SiC MOSFET can be analyzed by measuring the key parameters in the switching process (such as turn-on and turn-off time, oscillation and spike of current and voltage waveforms, etc.). Double-pulse testing is an effective method for examining the dynamic characteristics of power devices which used to assess the device's performance and the appropriateness of the setting of the main parameters of the drive circuit. The reasons why double pulse testing is adopted to analyze the switching process of SiC MOSFET are as follows:

Fast switching process: SiC MOSFET has the characteristic of fast switching. Double pulse testing can better capture the details of its switching process, including rise time, fall time, transition process, etc.

Evaluate switching characteristics: Double pulse testing can help evaluate the switching characteristics of SiC MOSFET, such as switching losses, switching waveforms, switching efficiency, etc., which is crucial for designing and optimizing power electronic systems.

Accurately measure key parameters: Through double pulse testing, key parameters of SiC MOSFET, such as on-state resistance, off-state resistance, and switching time, can be accurately measured, which helps an in-depth understanding of the device's performance.

Validate model accuracy: Double pulse testing can be used to validate the accuracy of the circuit model of SiC MOSFET, thereby improving the reliability of simulation results.

The schematic diagram of the double pulse circuit is shown in Fig.3. Since the gate-source voltage and device switching performance are not easily affected by parasitic parameters, the switching performance of SiC devices is usually regulated by adjusting the gate drive circuit parameters, such as gate drive resistance and drive voltage. In the following, the switching features of SiC MOSFET is investigated under different gate drive circuit parameters in an operating environment with a bus voltage of 800V.

4.1 Influence of driving resistance on switching characteristics

The driving resistance R_g is directly related to the switching time, switching loss and voltage and current waveform of SiC MOSFET. As shown in Fig.4, when the driving positive voltage is 20V and the driving negative voltage is-5V, the switching waveforms of SiC MOSFET are observed by changing the driving resistance in the on-state and off-state respectively. From the simulation results, with the increase of the driving resistance, the turn-on and turn-off speeds of SiC MOSFET decrease, and the turn-on and turn-off delay also increase with the increase of the driving resistance.

With the increase of the driving resistance, the rising rate and falling rate of the drain current I_d decrease, and the rising rate and falling rate of the drain-source voltage V_{ds} also decrease. In furthermore, the oscillation degree of the turn-on and turn-off waveforms is reduced, and the voltage spike of the drain-source voltage V_{ds} is also reduced.

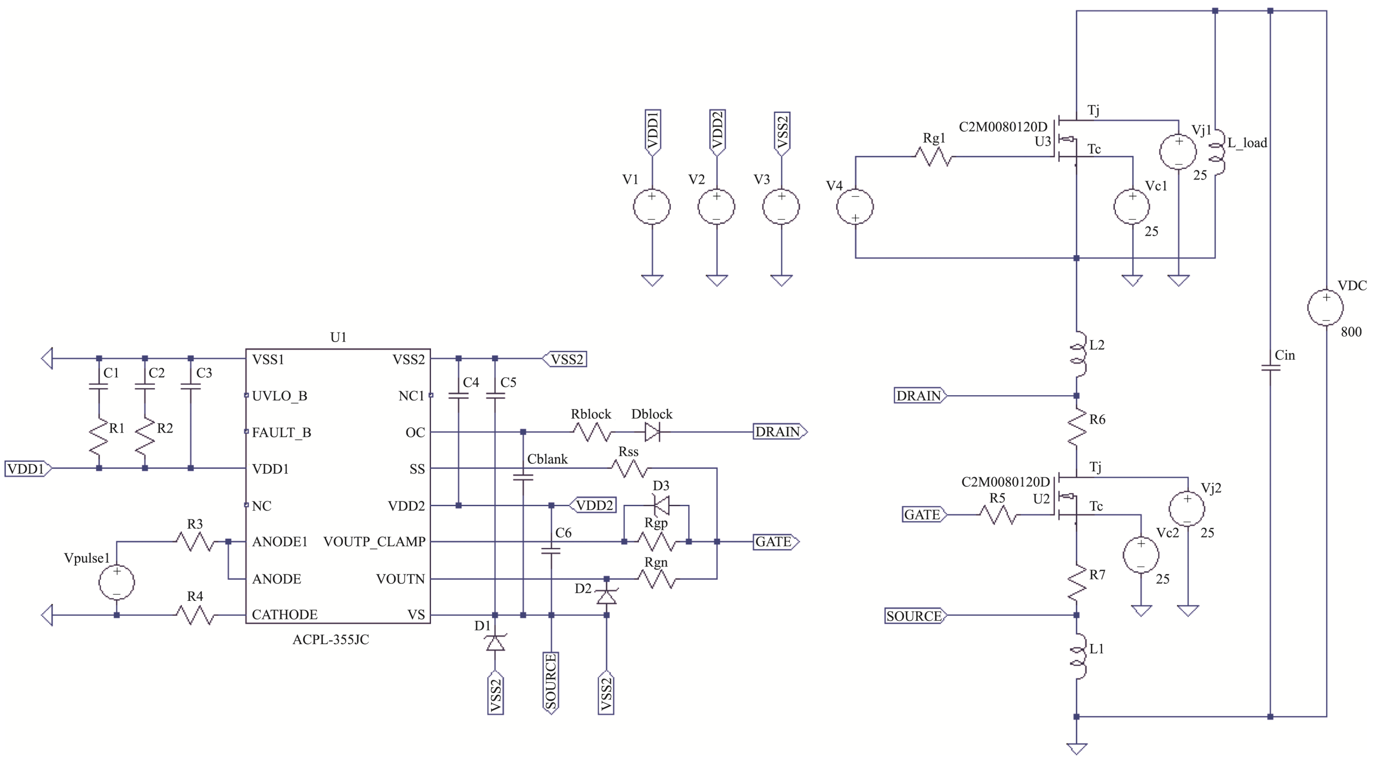
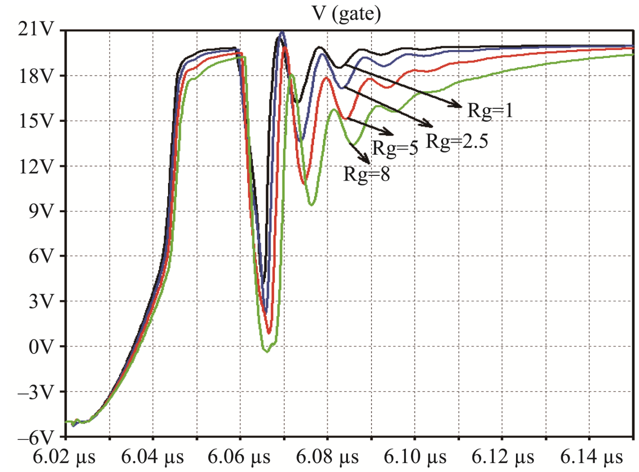
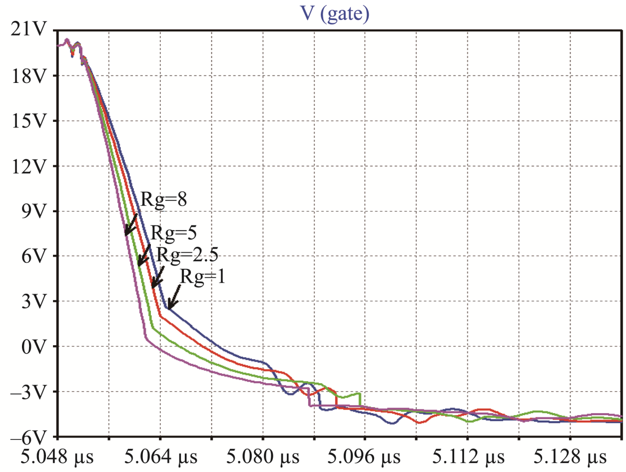


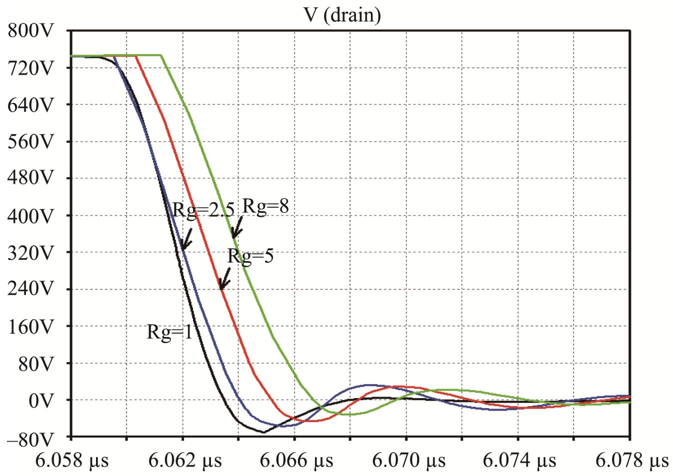
Fig.3 Double pulse circuit schematic



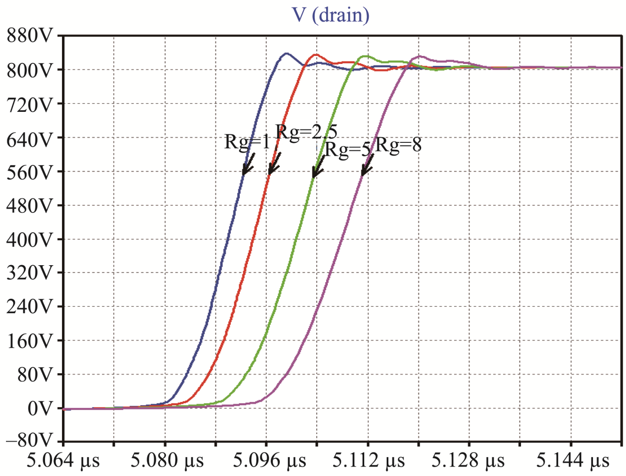
(a) Turn-on drive waveform



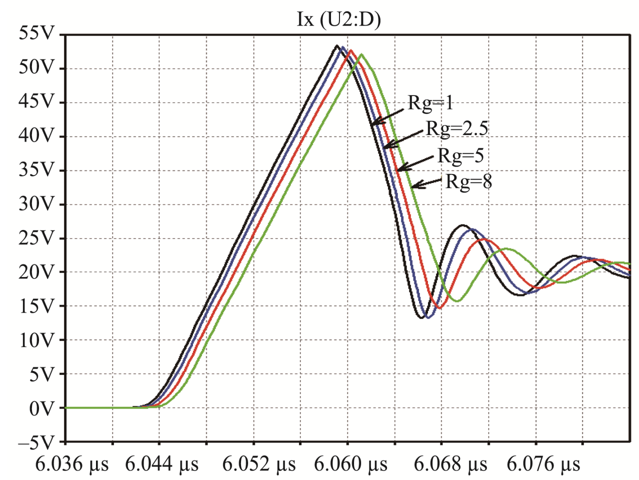
(b) Turn-off drive waveform



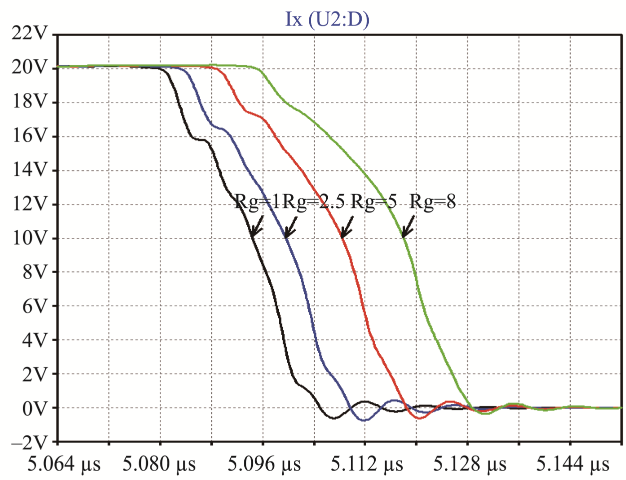
(a) Turn-on voltage waveform



(b) Turn-off voltage waveform



(a) Turn-on voltage waveform



(b) Turn-off voltage waveform

Fig.4 Experimental waveform of switching process with different driving resistors

The following table shows the switching time of SiC MOSFET under different drive resistors. The voltage rise time is defined by the data sheet as the time from 10% of the first rise to 90%, and the voltage drop time is defined as the time from 90% of the first drop to 10%.

Table 3 SiC MOSFET switching time with different driving resistors

	R_g=1	R_g=2.5	R_g=5	R_g=8
Rise time t_r (ns)	3.25	3.69	3.91	4.33
Fall time t_f (ns)	11.82	12.81	14.29	16.09

4.2 Influence of driving voltage on switching characteristics

As shown in Fig.5, by changing the driving positive voltage and the driving negative voltage, the switching waveforms of SiC MOSFET are observed under the on-state and off-state when R_{gon} = 2.5Ω and R_{goff} = 1Ω. From the simulation diagram, the turn-off characteristics of SiC MOSFET are changed by the change of driving negative voltage. While the driving negative voltage value increases, the turn-off speed of the device does not increase significantly. However, the device turn-off loss is reduced, the drain-source voltage and drain current turn-off delay is reduced and the response becomes faster. The device turn-on gate-source voltage and drain current waveform spikes are reduced, and the drain-source voltage turn-on delay is reduced.

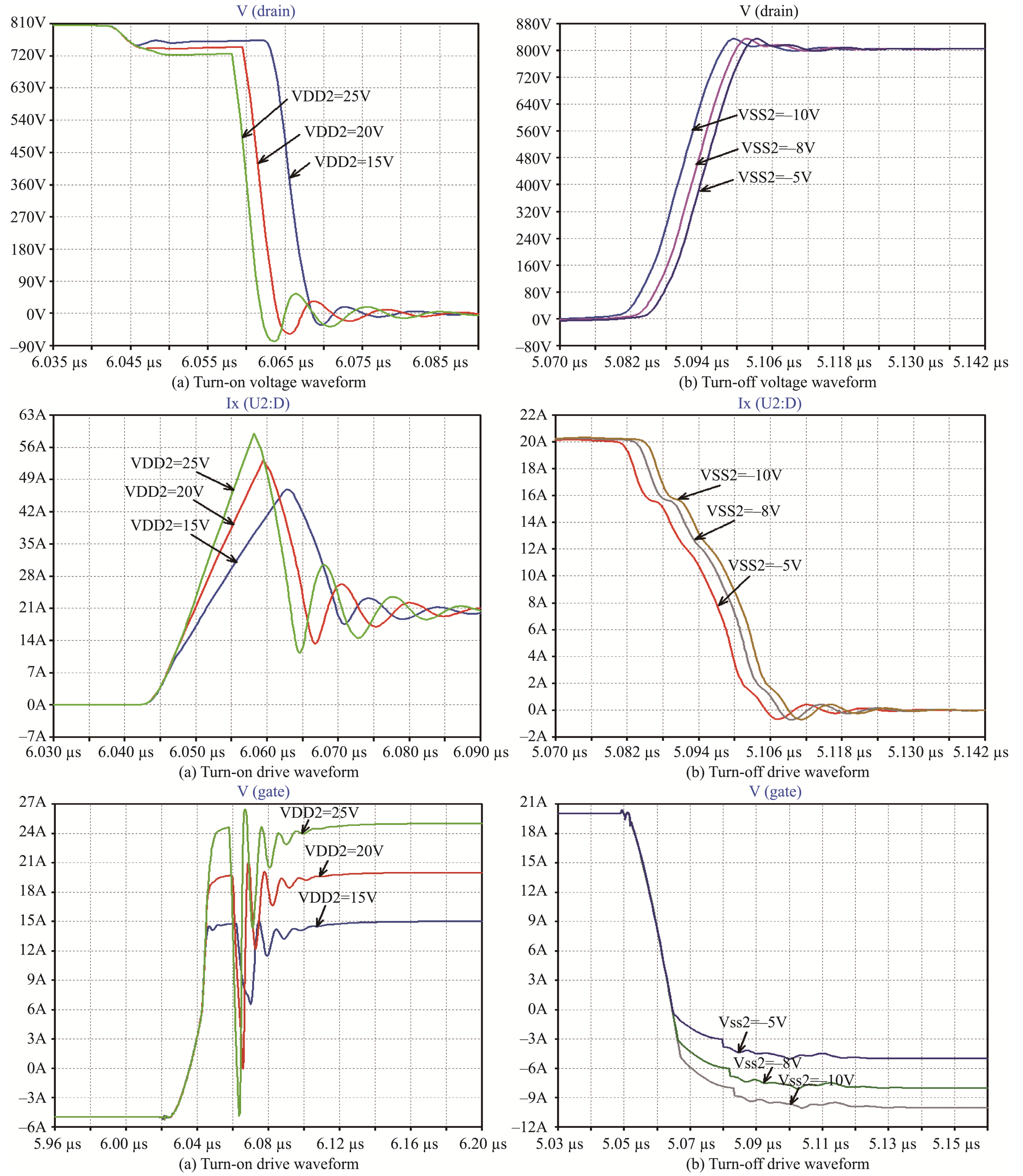


Fig.5 Experimental waveform of switching process with different driving voltage

The turn-on characteristics of SiC MOSFET are significantly affected by the driving positive voltage. With the increase of the driving positive voltage, the turn-on speed of the device is accelerated, and the change rate of the drain-source voltage and the change rate of the drain current increase. There is no significant change in the device turn-off speed, but the drain-source voltage turn-off delay increases and the response becomes slower. However, too high driving voltage will further increase the driving loss, reducing the driving reliability.

The following table shows the switching time of SiC MOSFET under different driving positive voltages.

Table 4 SiC MOSFET switching time with different driving voltage

	V_{DD2}=15V	V_{DD2}=20V	V_{DD2}=25V
Rise time t_r (ns)	4.81	3.69	3.16
Fall time t_f (ns)	11.67	11.68	11.69

5 Conclusion

This paper focused on the research basis of the analysis of SiC MOSFET characteristics, which mainly discusses the design requirements and design principles of SiC MOSFET drive circuit. Then, the drive circuit is optimized based on the ACPL-355JC optocoupler drive module, and the drive circuit is verified by LTspice simulation software. The switching characteristics of SiC MOSFET under different working conditions, such as driving resistance and driving voltage, are studied in depth. The results show that compared to a switch circuit, the switching waveform oscillations in the SiC MOSFET switching process with a driver circuit are significantly reduced, and the switching time is also improved. Then, as the driving resistance increases, the rate of rise and fall of the drain current I_d decreases, while the rate of rise and fall of the drain-source voltage V_{ds} also decreases. In addition, the degree of oscillation of the turn-on and turn-off waveform is mitigated, and the voltage spike of the drain-source voltage V_{ds} is reduced. When the driving positive voltage is gradually increased, the device turns on faster and the rate of change of the drain-source voltage and the rate of change of the drain current increase. When the negative drive voltage is gradually increased, the device shutdown speed does not change significantly, the shutdown loss is reduced, and the drain-source voltage and drain current shutdown delay are reduced, and the response becomes faster.

Author Contributions:

Wenjie Li: Responsible for collecting relevant research materials, organizing literature, designing experiments, analyzing experimental data, and then writing the paper. Tianhu Wang: Determine the topic and research direction of the paper, oversee the experimental process, and conduct the final review and polishing of the completed manuscript. Jungang Wang, Tailiang Yu: Provide the necessary platform support for the experiment and assist in the analysis of experimental results.

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Data Availability:

The authors declare that the main data supporting the findings of this study are available within the paper and its Supplementary Information files.

Conflict of Interest:

The authors declare no competing interests.

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