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A study on electrical properties of silicon carbide power devices

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Abstract. Silicon Carbide (SiC) devices have the characteristics of high voltage resistance, fast switching speed, high working frequency, small on-resistance, and high-temperature resistance, and have broad application prospects in high voltage and high-power occasions. However, the application of SiC is faced with the problems of high-frequency switching transient voltage, current overshoot, ringing, and short circuit protection. Based on the problems encountered in the application process of SiC power devices, the characteristics and drive protection technology of sic devices are studied in this paper. In this paper, the static characteristic parameters of SiC device are studied, the switching characteristic parameters are tested, the influence of parasitic inductance parameters on the switching characteristic is analyzed, and the design method of PCB Roche coil is analyzed, the anti-interference performance of loop winding turns is analyzed and the driver protection circuit is designed.

Keywords: silicon carbide power devices, PCB Rogowski coil, driving design, short-circuit protection design.

1. Introduction

Power electronic devices have a very important impact on People's Daily life. This device is widely used in electric power, energy, communication, aerospace, and transportation [1]. Power electronic devices play a very important role in improving the overall performance of the device. With the development of technology, power electronic devices are gradually developing in the direction of high efficiency, high power density, high reliability, and low cost [2]. The traditional Si semiconductor materials are gradually approaching the theoretical limit, which limits the performance improvement of electronic and power devices. Compared with the traditional Si Mosfet, silicon carbide devices have the advantages of high voltage resistance, fast switching speed, high frequency, small on-resistance, and good high-temperature resistance [3]. Silicon carbide has many characteristics and advantages and has a wide application prospect in electronic and power devices, but its application has technical difficulties to be solved [4]. The increase in the switching frequency of SiC devices increases the difficulty of driver design. High dv/dt and di/dt make the parasitic parameters affect the switching characteristics of SiC devices more and lead to Electromagnetic Interference. The parasitic inductance generated by the device package structure and interconnect lines in high-speed products form a resonant loop with the junction capacitance of the device and stray capacitance of the line, resulting in voltage and current overshot and ringing, affecting the reliable use of SiC devices and limiting the switching frequency of SiC devices [5]. Because the new packaging technology is still in the theoretical and experimental stages, optimizing the circuit layout structure is very important. In order to give full play to the advantages of SiC devices and promote their application and promotion, we need to deeply study the characteristics of SiC devices to provide a basis for the design of drive protection [6]. Drive protection is the key to ensuring the reliable application of SiC devices, is the core technology of efficient and reliable application of SiC devices and is also one of the most core technologies of power electronic devices [7].

The first part of this paper introduces the development history, characteristics, advantages, and application prospects of SiC devices [8], and points out that there are urgent problems to be solved in the application of SiC devices. The second part introduces the current research status of SiC device short circuit protection, compares and analyzes the advantages and disadvantages of various short circuit protection methods, and tests the SiC power module, which provides a basis for the design of drive protection. Firstly, the static characteristics of SiC devices are tested, and then the switching characteristics of SiC devices under different bus voltages and load currents are tested. In addition, the influence of key parasitic inductance parameters on the switching characteristics is analyzed. The third part introduces PCB Rogowski coil [9], deduces the impedance characteristic parameters, and analyzes the anti-interference performance of PCB Rogowski coil with back-winding turns. The fourth part completes the design of the driver and short circuit protection circuit [10], and introduces each part of the driver circuit, including the power system, isolation design, the design of the driver circuit and soft shutdown, and the post-stage signal processing circuit of PCB Rogowski coil.

2. Study on basic characteristics of silicon carbide power devices

Due to the different properties of semiconductor materials, there are some differences in electrical characteristics between SiC and Si power devices. In order to ensure the correct use of SiC power devices, give full play to their characteristic advantages, and make the sic power device-based converter system can obtain better performance, we need to deeply analyze and study the switching characteristics and parameters of SiC power devices, especially the switching characteristics.

In order to ensure the safe and reliable operation of SiC devices in practical applications, short circuit protection is very important. Many device manufacturers and driver manufacturers as well as many scholars have done research on the short circuit protection of SiC devices. They put forward some short circuit protection methods, mainly including the following. The first one is hidden voltage detection, that is, desaturation detection. This method is widely used in short circuit protection of Si IGBT. It is simple to design and easy to implement in the driver IC. The second is the ratio method MOSFET. It consists of tens of thousands of transistor cells in parallel. There are some MOSFETs used part of the parallel cell is connected to the common gate and drain, but separated at the source. This results in an isolated transistor, which we call a "detection" transistor. The third is source inductance detection. When the device is short-circuited, the rapidly changing current creates a voltage drop across the source parasitic inductor Ls, which is used to detect the current. The fourth is detection resistance. The detection resistor is connected to the source pole of the device in series. The current flowing through the resistor will generate a voltage signal to determine the short-circuit fault. The fifth is gate charge detection. The method uses the difference between gate-source voltage under normal conditions and short circuit faults to judge the short circuit fault. The sixth is Rogowski coil current detection. Rogowski coil is analogous to a current transformer. The static characteristic test mainly includes the output characteristic and transfer characteristic of the device and other static parameters of the device the number. When the gate-source voltage is between 18V and 20V, the device is basically on. At this time, if the driving voltage continues to increase, the driving loss will be increased, the short-circuit current will be increased, and the short-circuit tolerance time of the device will be reduced. When the gate-source voltage is below 16V, the device is not fully on. In this under the driving voltage, the on-state resistance of the device is very large, which causes the increase of on-state loss of the device and reduces the efficiency of the converter. In summary, the driving voltage of SiC devices is generally 18-20V. The saturation voltage drop of SiC devices is greatly affected by temperature for different temperatures and working currents. Under the same test current, the saturation voltage drop increases with the increase in temperature. Under 1500c and the voltage drop is about twice that of 25C under the same current condition. In the

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leakage current is 15mA test conditions, the SiC device threshold voltage and temperature relationship, compared with the specific values on the datasheet are different. The main reason is that the test condition of the device manual is 108mA, but the variation trend is basically the same. The threshold voltage of the SiC device is low and decreases with the increase in temperature, so at high temperatures, it is easier to cause device misdirection, which also increases the difficulty of driver design. Therefore, we should reduce the driving loop area and parasitic inductance as much as possible in the driving design. Moreover, the SiC MOSFET is more prone to short circuit breakdown when the threshold voltage decreases. Dual pulse testing is an important part of switching characteristics. Double pulse test (DPT) is to test the dynamic characteristics of power devices and obtain the main parameters of the switching process, such as rise time tr, fall time tf, di/dt of the opening process, dv/dt of the closing process and switching loss, etc. This is to evaluate whether the on-resistance Ron and off-resistance Roff values are appropriate, while testing the switch the overshoot and ringing of the process voltage and current meet the application requirements. The results of the dual-pulse test provide a basis for evaluating the switching performance of power devices and designing power electronic converters, such as switching frequency and dead-time selection, and efficiency evaluation. In the two-pulse experimental circuit (as shown in Figure 1), the upper tube parallel load inductor L gives the normally off signal. The lower tube is the Device under Test (DUT), giving width and narrow double pulse signals. Vdc is high voltage DC power supply, Kl is a high-voltage circuit breaker, and Rd is discharge resistance. The working waveform of the double pulse circuit is shown in Figure 2. Because the dual-pulse test switch is only opened twice, the junction temperature rise due to switching loss is negligible.

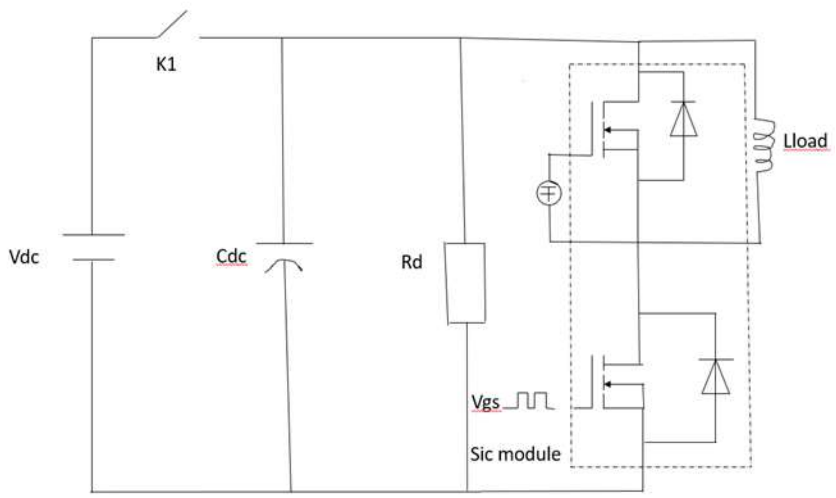

Figure 1. Schematic diagram of double pulse circuit.

The test process is as follows: we close the circuit breaker KJ, wait for the capacitor to charge to the set value and disconnect, and at the same time carry out double pulse test on the trigger signal. We waited for the discharge of the DC bus capacitor, recharged the capacitor, changed the bus voltage setting value, and repeated the experiment process. The load inductance is 409H, and the double-pulse switching time is l0micros / 3micros / 3micros respectively. Considering the switching speed of the device and the voltage and current overshot and ringing of the device, the gate resistance Ron=2.5ohm and Roff=5ohm were finally determined through testing. Parasitic inductance has a great influence on the switching characteristics of SiC devices. In practical converters, the parasitic inductance in the circuit mainly comes from the SiC power device package and PCB layout connection line.

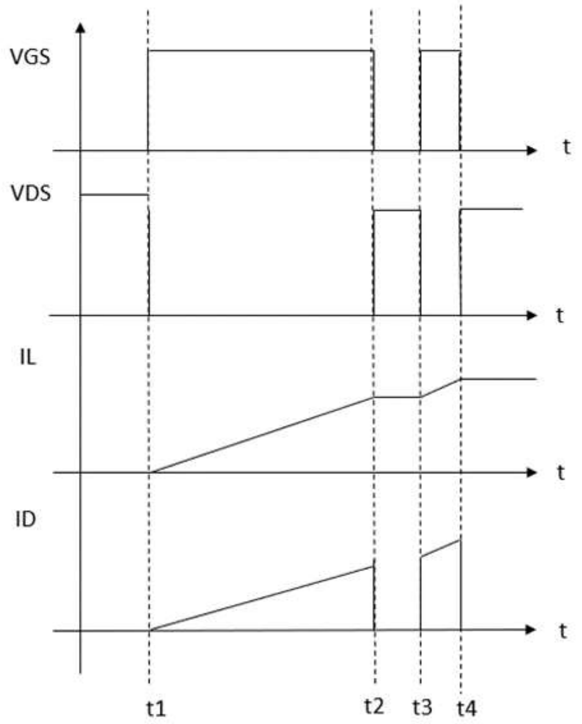

Figure 2. The working waveform of the double pulse circuit.

3. Study on PCB Rogowski coil

The traditional Rogowski coil is made by winding the wire on the skeleton made of non-magnetic material by hand or winding machine, so uniform winding density and fixed cross-sectional area cannot be guaranteed. This leads to its poor repeatability, large dispersion, and the stability of mutual inductance coefficient, the consistency of distribution parameters and anti-interference can not be effectively guaranteed. And PCB Rogowski coil realizes digital wiring and fully automated production. It overcomes the inherent shortcomings of the traditional Rogowski coil and has the advantages of structural parameters, system stability, high-frequency bandwidth, measurement sensitivity, and precision. The loop winding design of Rogowski coil is to wind the coil in the opposite direction on the back of PCB after winding the coil once and then it returns to the output end. The current of Cree 1700V / 300A SiC power module CAS300M17BM2 is detected by the method shown in Figure 3. Rogowski coil passes through the drain pole of the upper tube and the source pole of the lower tube respectively to measure the current of the upper and lower tubes of the power module. The layout of coils in PCB is realized as shown in Figure 4. Four-layer circuit board is adopted, in which the top and bottom layers are copper foil for coil wiring, while the middle two layers are loop-winding turns, and each layer is connected through the via hole.

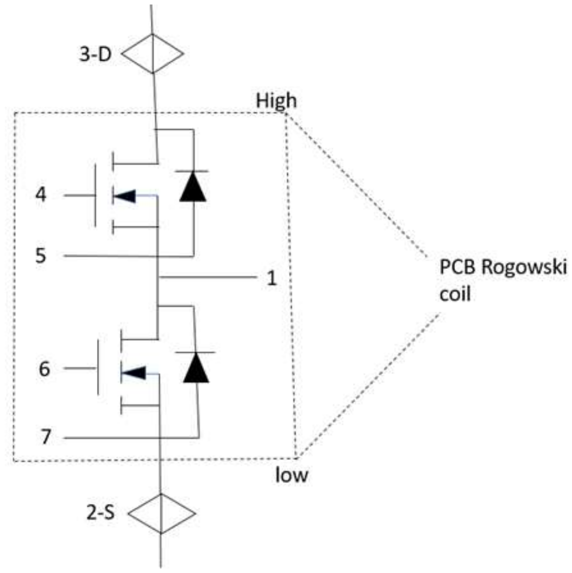

Figure 3. PCB Rogowski coil current detection method.

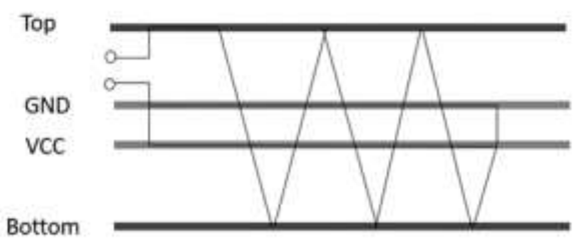

Figure 4. The layout of coils in PCB

PCB Rogowski coil should be designed to ensure its stability and reliability and to ensure the accuracy of measurement. The specific design requirements are as follows: the number of turns of the coil should be even. In this case, the flux chain of the current-carrying conductor to the coil is equal in size and opposite in direction, which can avoid the influence of the induced magnetic field of the coil itself on the current measurement. The mutual inductance of the coil is the most important electromagnetic parameter. Increasing the coil mutual inductance plays an important role in increasing the output voltage level, obtaining a stable output voltage signal, improving the anti-interference ability to external interference magnetic field, improving the probe signal-to-noise ratio, and improving the sensitivity and accuracy of the current measurement.

$$M = \frac{\mu_0 N h}{2\pi} ln\left(\frac{R}{r}\right) \quad (1)$$

According to Formula (1), the mutual inductance parameters of Rogowski coil are related to the number of coil turns N, PCB plate thickness h, and the ratio R of coil outer diameter to inner diameter. Therefore, under normal circumstances, we can increase the mutual inductance of coils from the following aspects. 1. Increase the number of coil turns. Increasing the number of coil turns leads to more holes and denser wiring copper foil. The SiC module used in this design is the industry standard 62ram package housing. Because the Rogowski coil needs to be used with the SiC module, the number of turns of the coil cannot be increased arbitrarily due to the limited coil wiring space and PCB manufacturing process. 2. Increase PCB board thickness h. Considering the hole utilization and manufacturing process limitations, PCB board thickness is generally not more than 3mm. 3. Increase the ratio of the outside diameter and the inside diameter of the coil, that is, increase the outside diameter of the coil or reduce the inside diameter of the coil. Wiring space and manufacturing process constraints are also considered. The above methods need reasonable design, not only to ensure that the production is easy to realize but also to meet the requirements of wiring space.

4. Driving design and short-circuit protection design

The driving voltage of SiC devices is higher than that of Si devices. Generally, the gate-to-source voltage is between 18V and 20V, which can ensure the device conduction and the conduction resistance is small. The threshold voltage of SiC devices is low and decreases with increasing temperature. Therefore, in order to avoid the crosstalk leading to the misdirection of the device at high frequency, the negative voltage turn-off is used to ensure its safe working range. At the same time, we should ensure that the driver has enough driving capacity to meet the requirements of driving power and driving current. Second, the SiC switching frequency is high, the drive needs to meet the high frequency switching requirements of the SiC device, and the rising and falling edges of the drive pulse should be steep enough. Moreover, the switching loss and switching oscillation are closely related to the switching speed of the device, and the switching speed is usually determined by the design of the driver. The switching characteristics of the device should be regulated by adjusting the parameters of the gate drive circuit. In addition, the design of the drive circuit should optimize the layout structure of the drive circuit to ensure that the parasitic inductance of the gate drive circuit is as small as possible. In addition, the drive circuit should be equipped with electromagnetic interference (EMI) resistance, which is crucial in high-speed operating conditions. Figure 5 shows the driver protection circuit structure of SiC MOSFET. It mainly includes power module, isolation part, power amplification, soft shutdown design, and short circuit protection.

The block diagram of the power supply system designed for the driving circuit is shown in Figure 6.

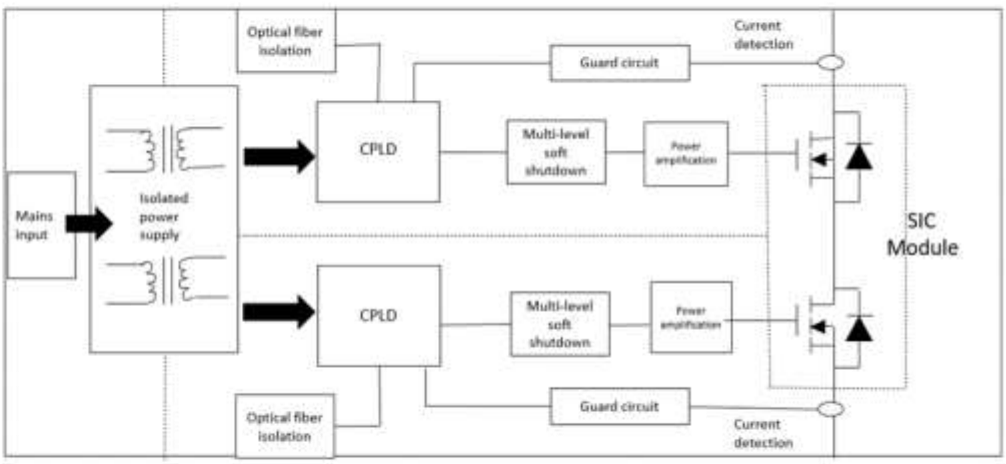

Figure 5. The Driving structure block diagram of SiC.

We use flyback converter to achieve multiple voltage output. The input voltage is rated at 15V, and three output voltages are generated. 23V provides the positive driving voltage of the power amplifier circuit, and -8V provides the negative driving voltage of the power amplifier circuit. The voltage set here is higher than the designed 20V / -5V due to the voltage drop at the collector and emitter of the triode. ±8V supplies power to the chip in the signal processing circuit, and 5V is generated by the power chip to supply power to the built-in CPLD.

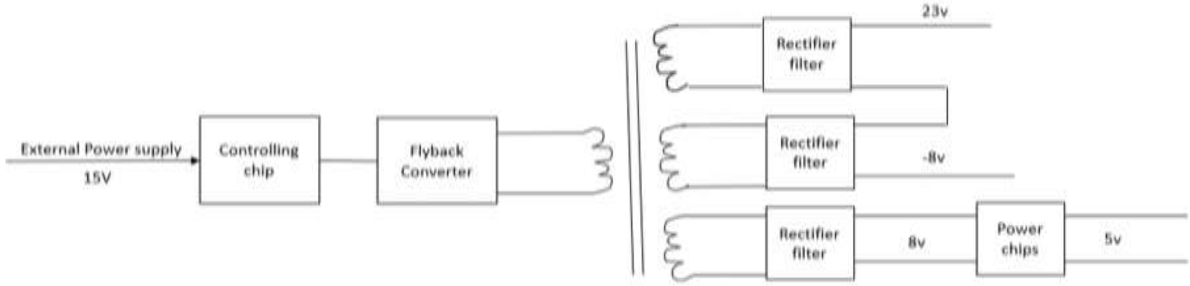

Figure 6. The Block diagram of the power supply system structure.

Because the power supply adopts transformer isolation, the actual equivalent model of the transformer considering parasitic parameters is shown in FIG. 7. Here we are mainly concerned with the effect of stray capacitance. Among them, C13, C14, C23, and C24 are primary/secondary interwinding capacitors. C12 and C34 are primary/secondary intrawinding capacitors. These constitute the coupling capacitance between primary and secondary sides of the transformer.

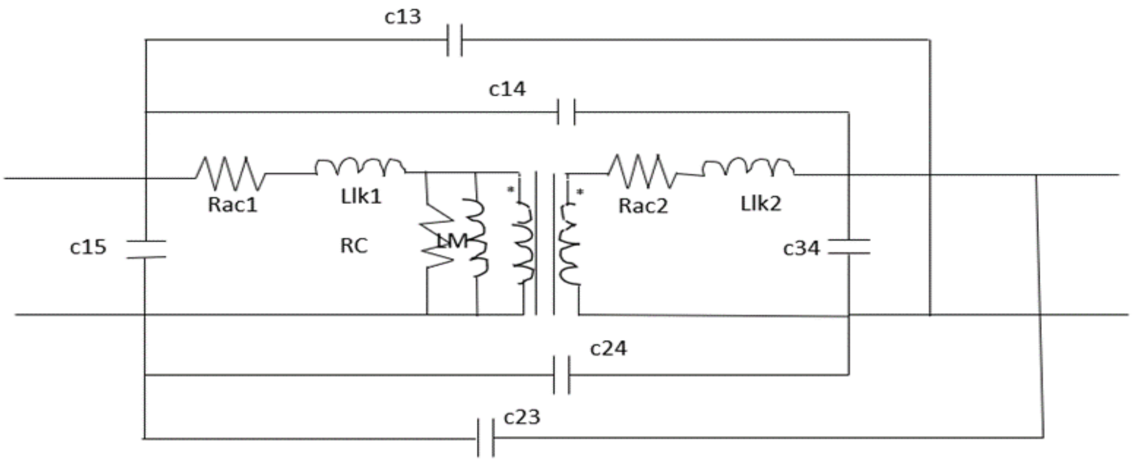

Figure 7. The transformer equivalent model considering parasitic parameters.

The security of SiC devices must also be considered. Usually, SiC devices work under high voltage of hundreds of volts or even thousands of volts, so it is necessary to achieve safe and reliable isolation of control circuit and drive circuit. The commonly used isolation methods usually include level shift bootstrap isolation, optocoupler isolation, transformer isolation, and optical fiber isolation. The level shift bootstrap isolation circuit is simple and low cost, but the isolation voltage level is generally not higher than 600V, which is not suitable for high voltage applications. Optocoupler isolation is often used in the design of driving circuits. In this design, long-distance transmission is required, the isolation voltage is high, and the electromagnetic interference is strong in high-voltage and high-power applications. Therefore, optical fiber isolation is adopted, as shown in Figure 8. The PWM control signal is connected to the drive board through the optical fiber receiver, and the fault information is fed back to the main control board through the optical fiber transmitter after the short-circuit fault occurs.

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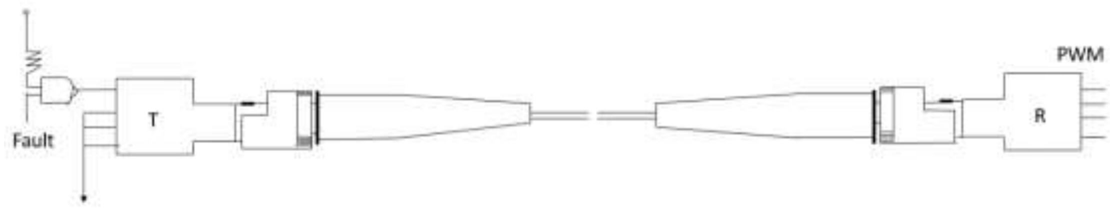
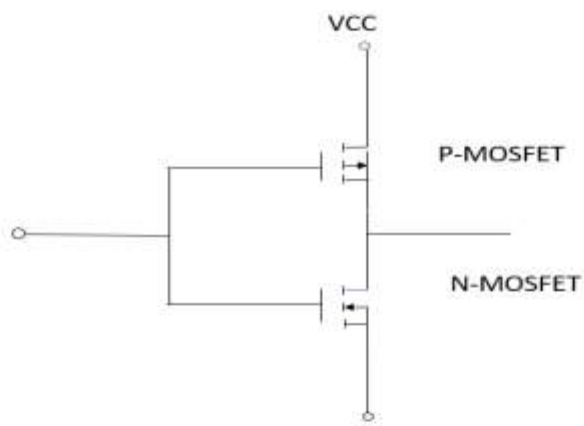


Figure 8. Fiber isolation mode.

The realization of the driver circuit is generally divided into two kinds: integrated driver chip and discrete device-built circuit. In general, the integrated driver chip is simple to use. It only needs to build a simple peripheral resistor, but the range of choice for SiC devices is small. Using discrete devices to build the driver circuit is more flexible and applicable to a wider range. Generally, push-pull circuits as shown in FIG. 9,10,11 are used for power amplification. One is the use of MOSFET push-pull circuit, the actual use of P-type MOSFET is less and not easy to buy, and MOSFET switches need to have enough voltage, need additional driver design, its circuit complex. Moreover, the MOSFET turn-off has a delay, which has a bad influence on the drive control of SiC devices. The other is NPN and PNP triode composition push-pull circuit, the upper tube is NPN type, and the lower tube is PNP type, this is the most commonly used structure of power amplifier circuit. It has the advantages of simple structure and low cost.



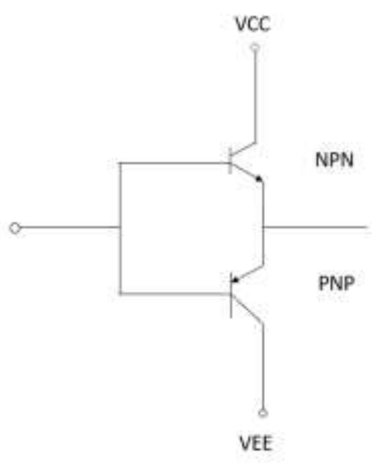


Figure 10. The power amplifier of BJT.

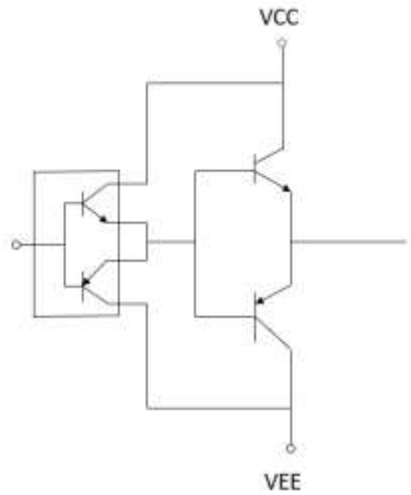


Figure 11. The power amplifier of two stages.

The gate resistance connection mode as shown in FIG. 12 can adjust the on and off resistors to adjust the on and off characteristics of SiC devices respectively. In order to prevent electrostatic breakdown of the device, the resistor is usually connected in parallel at both ends of the gate-to-source pole, and its value is generally tens of Kohm. At the same time, in order to prevent the gate-source voltage from being raised on the bus without driving voltage, the gate-to-source voltage will be raised through the Miller capacitor, which will cause the device to mislead and damage the device. In addition, when the gate-to-source voltage exceeds the safe voltage range, the device will break down and damage the device. Therefore, the gate-to-source voltage needs to be protected. When the SiC device works normally, the current is not large and the hard turn-off overvoltage is not very high, which generally does not cause device damage. But when the short circuit fault occurs, the short circuit current value is very large, generally 8 to 10 times the rated current, or even higher. In order to avoid the voltage spike caused by hard turn-off when short circuit occurs. On the one hand, we can reduce the parasitic inductance of the power loop by optimizing the circuit layout structure to suppress the turn-off overvoltage, and on the other hand, we can use the soft turn-off method to reduce the current change rate during the turn-off process.

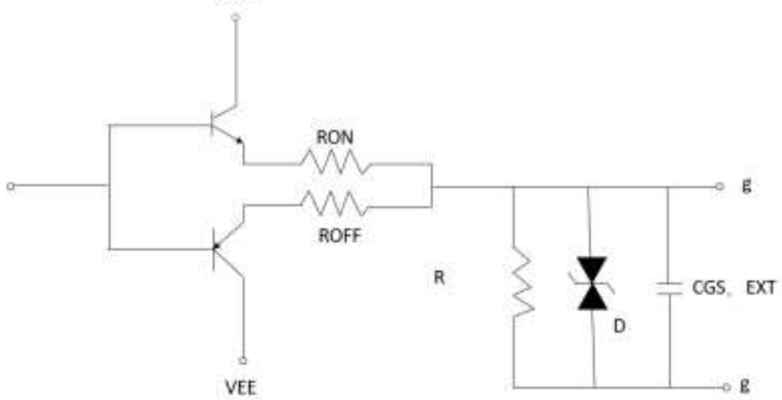


Figure 12. The driving mode of gate-to-source.

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5. Conclusion

SiC devices will be widely used in high-power electronic converters. Despite the advantages of SiC devices, there are some problems with their application. This paper focuses on solving the application problems of SiC high frequency switching transient voltage, current overshoot, ringing and short circuit protection. The device characteristics and drive protection of high power SiC MOSFET are studied. This paper introduces the characteristics, advantages, development history and application prospect of SiC devices. At the same time, it is pointed out that there are some problems that need to be solved in the application of SiC devices. The influence of temperature on the static parameters such as saturation voltage drop, threshold voltage and on-state resistance of SiC devices is studied, which provides the basis for the design of drive protection. In this paper, the existing problems of traditional desaturation detection method in SiC short circuit protection are analyzed. The desaturation characteristics of SiC MOSFET are not obvious, the short circuit tolerance time is short, and the output characteristics are greatly affected by temperature. In this paper, the short circuit protection scheme based on PCB Roche coil current detection is adopted and the design of driving protection circuit is completed

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