Semiconductor Switch: Key Components and Future Developments in Power Electronics

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Abstract. The rapid development of modern industry has led to the expansion of the demand for high-end devices in a wider range of fields. Semiconductor switches have also become a popular research area as key components in electronic engineering. It also plays an important role in controlling current and regulating power transmission. The performance requirements for semiconductor switches have gradually increased to meet higher current controlling and power transmission requirements. This paper provides a comprehensive introduction to the basic operating principles and structural components of semiconductor switches, compares the characteristics and applicable scenarios of common types of switches, including metal-oxide-semiconductor field-effect transistor (MOSFET), bipolar junction transistor (BJT) and insulated-gate bipolar transistor (IGBT), and the emerging types of semiconductors switching devices in recent years. The paper also concerns the key parameters affecting their performance and their applications in power electronics. Finally, recent research progress in the field and future research trends are reviewed as well.

1 Introduction

With the rapid development of electronic technology, semiconductor switches, as a core component in the field of power electronics, have become an indispensable part of modern power systems. These devices play a key role in a wide range of fields, from home appliances to high-end industrial control systems, and have greatly contributed to the advancement of power conversion technology. Globally, the rapid evolution of semiconductor switching technology has been driven by continuous research in material science, device structure optimization, and application technology in different countries and regions.

In recent years, the development of semiconductor switches has been quite rapid. Related researchers at home and abroad have developed many new types of semiconductor switching devices. The continuous development of modern industry has brought about higher standards for the working environment and performance of the original components. On the basis of the original semiconductor switching devices, new switching devices suitable for more extreme environments have also come into being.

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The purpose of this paper is to provide an overview of domestic and international research progress on semiconductor switching devices, with a comprehensive review from structural characteristics, operating principles to applications in different power electronic systems. The article begins with a review of the technological development of semiconductor switching devices focusing on the evolution from thyristors to modern IGBT and MOSFET and compares the main research results and application practices in this technology area in different countries. Subsequently, this paper provides an in-depth discussion of the latest international research developments in new semiconductor materials. It also explores efficient device design and intelligent control strategies. These technological advances address the challenges facing modern power systems.

2 Basic principles and structure of semiconductor switching devices

Semiconductor switching devices are very effective electronic components for controlling the flow of current, and their basic function is to act as switches between on and off states. Semiconductor switching devices are made up of three basic components based on their type of construction: a control terminal (gate or base), an input terminal (source or emitter) and an output terminal (drain or collector).In the presence of voltage, the control terminal affects the conductivity of the PN junction, thus controlling the flow of current [2].This capability makes Semiconductor switching devices play a vital role in circuit design, especially in applications that require fast switching of current states. The structures of common Semiconductor switching devices are shown in Figure 1 and Figure 2.

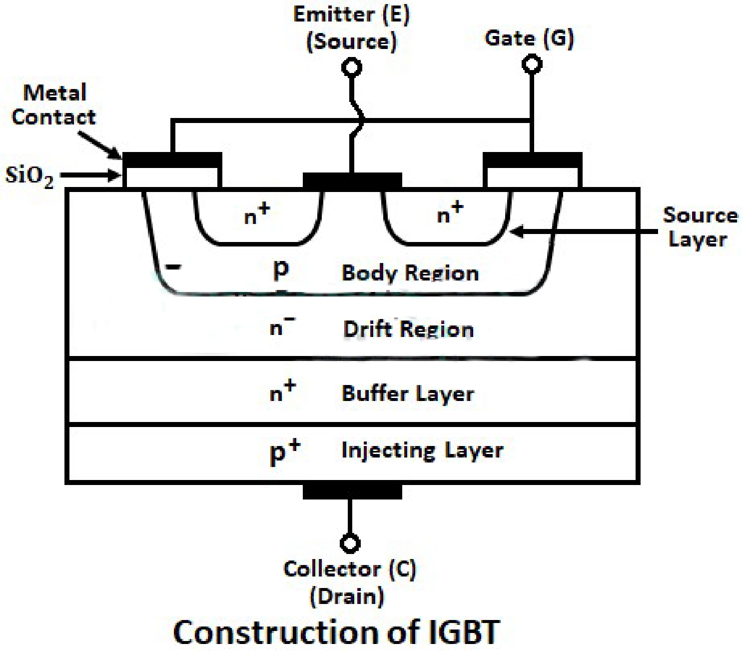

Figure. 1. Structure of IGBT[1].

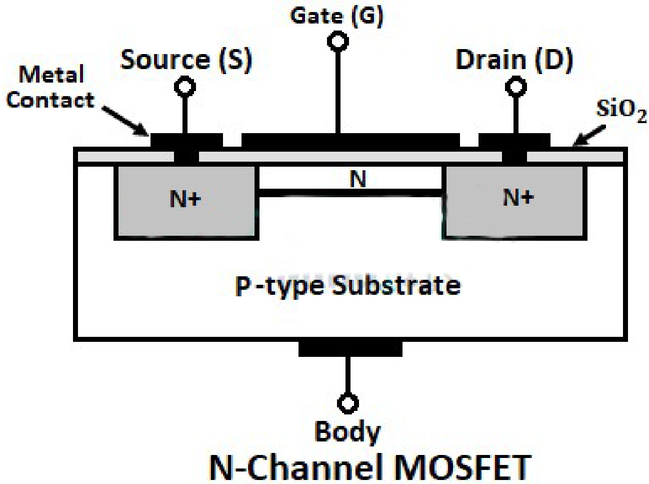

Figure. 2. Structure of MOSFET [1].

3 Common types of semiconductor switching devices

Among the many types of Semiconductor switching devices, MOSFETs, IGBTs and SiC MOSFETs are some of the most common. MOSFETs are widely used in small electronic devices for their low power consumption and high frequency response. IGBTs, on the other hand, combine the high efficiency of MOSFETs with the high current-carrying capacity of conventional bipolar transistors, making them suitable for high-power applications such as electric vehicles and solar inverters. SiC MOSFETs take advantage of the excellent properties of silicon carbide to provide higher temperature tolerance and lower energy loss for applications in high-voltage and high-temperature environments. In addition, there are many other types of semiconductor switches, such as photoconductive semiconductor switches, which have attracted a lot of attention in high-speed diagnostics, detection, signal processing, and high-power ultra-wideband microwave generation. Because they have a series of excellent optical and electrical characteristics that are not found in conventional switching technologies, such as fast conversion, low jitter, high power capacity, repeatable operation, optical triggering, immunity to electromagnetic interference, simplicity and reliability, small size, lightweight, and ease of array operation[2].

3.1 MOSFET

A MOSFET consists of a gate, a drain, and a source. The current between the drain and the source is controlled by applying a voltage across the gate to create an electric field between the gate and the source. When the gate voltage is zero, the MOSFET is at cut-off and there is no conductivity between the drain and source. When a positive voltage is applied to the gate, an electric field is formed that attracts charged carriers into the conducting channel, causing the MOSFET to conduct and current to flow from the drain to the source.The conductivity characteristics of MOSFETs are controlled by the gate voltage, resulting in higher switching speeds and lower on-resistance for high-frequency switching applications.

3.2 IGBT

The IGBT structure is similar to a MOSFET but incorporates a PN junction between the gate and drain to form a bipolar structure. When a positive voltage is applied to the gate, an electric field is formed that controls the on-off state of the PN junction. When the gate voltage is zero, the IGBT is in the cut-off state and there is no conductivity between the drain and the source. When a positive voltage is applied, the PN junction breaks down in the reverse direction, causing the IGBT to conduct and current to flow from the drain to the source.

IGBTs combine the advantages of MOSFETs and BJTs, such as: high efficiency and reduced energy consumption due to lower on-resistance and smaller on-state voltage drop. Because of its MOSFET input stage, the input impedance is extremely high and can be driven using lower current, reducing the complexity of the drive circuit and energy consumption. Its high voltage resistance makes it widely used in the field of power transmission and distribution. IGBT has good thermal stability, which makes it work well in extreme environments.

3.3 SiC MOSFET

SiC MOSFET refers to Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) based on Silicon Carbide (SiC) material[3]. It is a high-performance, high-temperature, high-frequency power semiconductor device for high-voltage, high-frequency, high-temperature and other demanding environments in power electronics applications. Compared with the traditional silicon-based MOSFET switch devices, it has more advantages, such as: high voltage tolerance, low on-resistance, high-temperature characteristics, high-frequency characteristics, and radiation resistance. These advantages allow it to match more working environments and become the optimal choice for MOSFET switching tubes. The structure of different MOSFET devices is shown in Figure 3 and Figure 4.

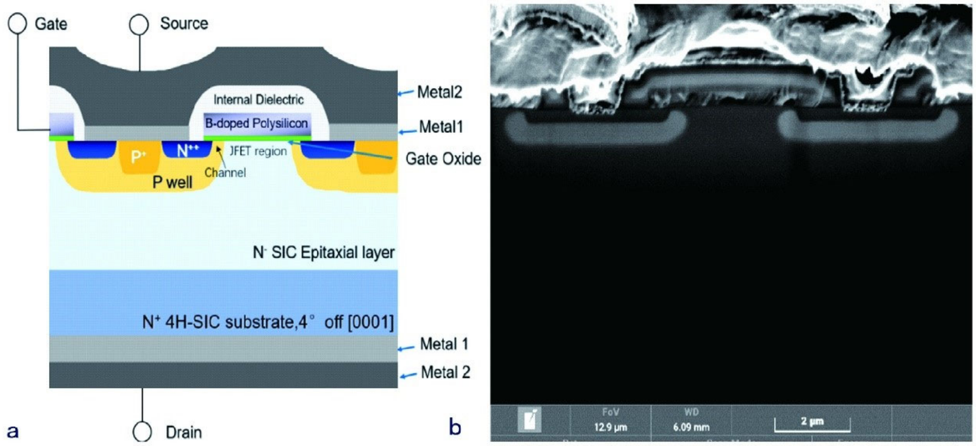

Figure. 3. Cross-section of the vertical SiC MOSFET [4].

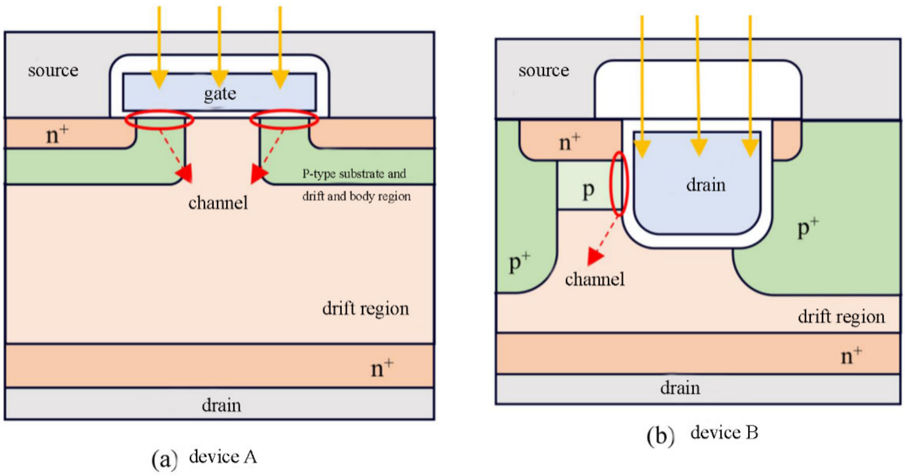

Figure. 4. Symmetric trench-gate SiC MOSFET and asymmetric trench-gate SiC MOSFET [5].

3.4 New sub-nanosecond cut-off semiconductor switch

This new sub-nanosecond cut-off semiconductor switching device is an ultrafast semiconductor cut-off switching device, which is composed of a four-layer structure of p+, p, n, n+. Experiments were carried out using devices with different initial Si resistivities, base region lengths, and pn junction depths. The main device parameters of the new sub-nanosecond cut-off semiconductor switch are shown in Table 1.

Table 1. Main parameters of the device [6].

V_R/kV	P_{peak}/kW	C/pF	t_{off}/ps	V_f/V	I_R/mA
⩾2	80	80	800	1.6(0.1mA)	⩽0.5mA

The new sub-nanosecond cut-off semiconductor switch successfully overcomes the drawbacks of conventional circuit breakers such as injected gates, bursting wires and plasma, which originally had nanosecond or microsecond cut-off times, such as short lifetime, poor shock resistance and inability to operate at repetitive frequencies. This new type of Semiconductor switching devices can be used on a large scale in the field of high speed and highway pulse technology.

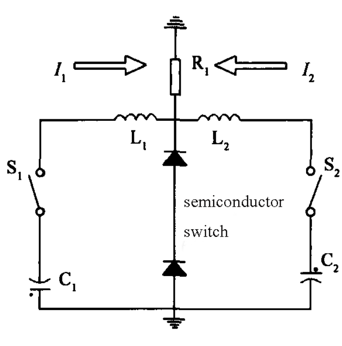

Figure. 5. Typical application circuit diagram for the switch[6].

Figure 5 Typical application circuit diagram for the switch[6]. But this new type of Semiconductor switching devices there are still technical shortcomings, the device sintering and traditional sintering process compared to a special requirement to solve the thermal stress of multi-layer Si sheet stack sintering, to ensure that the sintering process does not bring mechanical damage to the core itself, and the thermal stress to be matched, but also to ensure that the solder does not melt and the side walls of the core package.

3.5 RSD

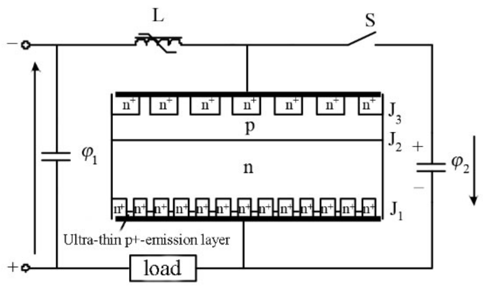

Figure 6. Ultra high-speed semiconductor switches RSD [7].

RSD is a new type of high-power ultra-high-speed Semiconductor switching devices, it is based on the trigger loop short-time reverse to achieve the switching characteristics of the opening makes it different from other traditional semiconductor switching devices. Its structure shown as figure 6 has a large area of fast and uniform turn-on, can be infinite series connection, high power, high commutation efficiency, long life, etc., in pulsed power technology has important applications

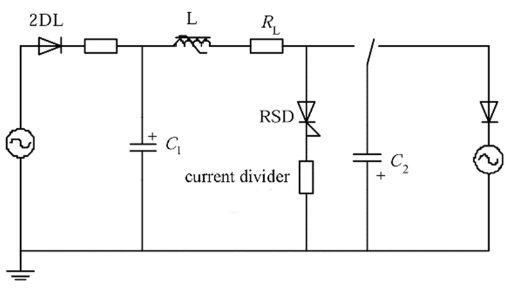

Figure. 7. Test bed principle for RSD turn-on characteristics [7].

The article used the test rig schematic shown in Figure 7 to test the turn-on characteristics of the RSD, measure the peak current allowed to pass through the RSD, and investigate the turn-on conditions and trigger loop.

Although it is experimentally found that due to the uniform synchronous turn-on of RSD switching devices, the commutation power is mainly related to the through-current area. Thus, the paper, the limit current test is carried out using a small-current chip. The large-current withstand of RSD switches with the same kind of structure and any through-current area can be obtained from the empirical formula. However, since most of the experiments used are idealized, the conclusions obtained are expected to have objective errors with the real situation.

4 Application areas of semiconductor switching devices

From power electronics to automotive electronics to industrial control, Semiconductor switching devices are increasingly being used in a wide range of applications. In power electronics, switching tubes are widely used to regulate efficient power conversion, such as in uninterruptible power supplies (UPS), solar inverters, and efficient power management systems in power grids for efficient energy transfer and distribution through fast switching and low energy consumption. With the popularity of electric vehicles, the application of switching tubes in motor control systems has become particularly important in the automotive industry. Especially, they are significant in modules, such as, battery management systems, drive motor control and on-board chargers for electric vehicles. These switches improve vehicle performance and range by boosting energy utilization and powertrain responsiveness. In the field of industrial control, switching tubes are used to precisely control the electric action of machines and equipment. They are used in frequency converters, servo drive systems, and robot control systems. Switching tubes achieve high-precision control of complex mechanical operations. They enable efficient operation of automated production. By providing stable power control and regulation capabilities, they ensure optimal performance. Semiconductor switching devices have become an important support for the development of key technologies in various industries due to their superior performance and wide application prospects.

5 Latest developments and future development trends

Performance parameters such as on-resistance, shutdown voltage and switching speed are key indicators for evaluating the performance of semiconductor switch tubes. The optimization of these parameters is directly related to the performance and stability of electronic equipment. The switching speed affects the response time of opening the tube, which is an important consideration for high-frequency switching applications.

In recent years, with the application of new materials such as GaN and SiC, the performance of semiconductor switch tubes has been significantly improved. The future development trend may revolve around the further optimization of energy efficiency, the improvement of high temperature resistance and high pressure, and the application of intelligent integration technology. These technological innovations will provide possibilities for semiconductor switch tubes in more demanding application environments.

5.1 DSRD

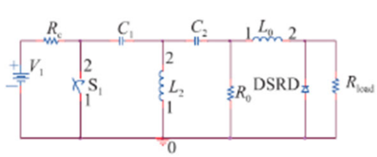

Figure. 8. DSRD-based pulse generator circuit structure[8].

This article analyzes the physical process of DSRD in detail and reveals the influence of device structure parameters on switching characteristics. The structure of DSRD-based pulse generator circuit is shown in figure 8. The author also designed a simple pump circuit to trigger a DSRD-based fast ionization switch (FID), and obtained an ideal pulse front end and high voltage output. Through in-depth analysis of the physical process of DSRD and the influence of device structure parameters on its switching characteristics, the author successfully realized the pulse voltage output of the fast leading edge, and designed a simple and effective pump circuit for triggering the switch of the FID[9]. hese research results provide important support and reference for the development of high-speed microwave technology, provide higher communication security, have stronger anti-interference performance and can be more accurate ranging, greatly enhance positioning capabilities, and promote the continuous development of modern communications, radar and navigation technology.。

5.2 Voltage performance improvement of high-voltage semiconductor switch components

The strong nonlinear voltage limiting circuit construction method has higher nonlinear ability and better voltage limiting effect than the traditional pure MOV circuit, and can effectively solve the problem of low static and transient voltage utilization in semiconductor switching components. In addition, an impedance matching circuit was added to the design process to solve the impedance matching problem and reduce the cost and volume[10].

This method can effectively solve the problems of overvoltage suppression and voltage limiting in semiconductor switching components, improve their static and transient voltage utilization, and also reduce cost and volume.This method can be applied to large-scale power electronic equipment, has a wide range of application prospects, and can provide technical support and solutions for the safe and stable operation of power systems, energy management, and the intelligent development of power grids.

6 Conclusion

This article comprehensively reviews the basic principles, common types and performance parameters of semiconductor switch tubes, and details their applications and challenges in different fields. By analyzing the latest technological progress and future development trends of semiconductor switch tubes, this article emphasizes its central position and future potential in modern electronic technology. The future development of semiconductor switching devices will focus on improving energy efficiency and improving high temperature and high voltage resistance. By optimizing the design and manufacturing process, as well as the use of new materials, it is expected that more efficient energy conversion and more stable performance can be achieved, so as to meet the needs of future power systems for efficient and reliable devices.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

References

1. Comparison Between SCR, BJT, MOSFET and IGBT, Electro. Min. (2022) Available online at: https://www.electronicsmind.com/comparison-between-scr-bjt-mosfet-igbt/
2. A. Rosen, F. J. Zutavern, High-Power Optically Activated Solid-State Switches. Artech House Boston, 1993. 1-296.
3. Y. Wang, Y.-M. Zhang, Y.-M. Zhang, X.-Y. Tang, A simulation study of 6H-SiC Schottky barrier source/drain MOSFET, Acta Phys. Sin. **52**, 2553-2557 (2003).

4. G. Yu, C. Huang, Detection of defects in the gate oxide layer of SiC MOSFETs, J. Electron Microsc. **43**, 190-199 (2024).
5. H. Shi, G. Guo, Z. Zhang, Proton single particle effect of SiC MOSFET, Semiconductor Technology, 1-7 (2024).
6. H. Ma, Z. Liu, Y. Yang, Development of a new type of sub-nanosecond cut-off semiconductor switching device, Semiconductor Technology, **35**, 337-339 (2010).
7. Y. Yu, L. Liang, M. Li, Research on the opening mechanism and high current characteristics of ultra-high-speed semiconductor switch RSD, J. Electro. Technol. 36-40+62 (2005).
8. G. Wang, F. Li, X. Jin, Working characteristics and experimental research on fast shutdown semiconductor switch, Strong Laser Particle Beam, **32**, 80-84 (2020).
9. R. Du, Y. Yu, Z. Peng, Newly opened principle of micro-nanosecond semiconductor switching device, China Electrotechnical Society. Proceedings of the Eighth Academic Conference of the Chinese Society of Electrotechnical Technology, Electric. Power. Press. **6** (2004).
10. K. Liu, Research on voltage performance improvement methods and applications of high-voltage semiconductor switching components, NCEP (2023).