Analysis of the Fabrication and Applications for State-of-Art MOSFET and JFET

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Abstract. Semiconductor devices have always played a vital role in the field of electronics, and their development has promoted the rapid progress of modern electronic technology. Among them, MOSFET and JFET are two important semiconductor devices, and their wide application in the electronic field leads technological innovation in different fields. This study will introduce the fabrication and application of these two mainstream FET devices, while analyzing their future limitations and prospects. Some improvements in structure and material of both devices will be introduced. The performance enhancements including I-V characteristic curve and energy loss are shown in this article. Studying the development, types, and progress of MOSFET and JFET provides insights into their history and advancements, contributing to improved device performance and reliability. Applications in integrated circuits, quantum computing, solar cells, biomedicine, and communication highlight their wide-ranging impact. To sum up, understanding FETs limitations and future prospects drives further innovation, advancing technology and electronic systems.

Keywords: MOSFET, JFET, SiC, energy loss.

1. Introduction

The concept of FET can be traced back to the early 20th century, Julius Edgar Lilienfeld proposed the early concept of FET. In his 1925 patent, he described the method and equipment about controlling electric currents, which include the concept of field effects controlling current flow [1]. However, the manufacturing technology of early FETs was not mature, so no practical devices came out. In 1947, physicists Walter H. Brattain and John Bardeen successfully invented the transistor at Bell Laboratories. On the basis of transistors, in 1952, William Shockley proposed the concept of JFET, which is a FET made of semiconductor materials. The working principle of JFET is based on the electric field control of PN junction. By applying a voltage across the PN junction, current flow can be regulated [2]. In 1959, Mohamed M. Atalla and Dawon Kahng first prepared silicon MOSFETs at Bell Laboratories, and published the paper in 1960 [3], which marks the birth of MOSFET as a key semiconductor device. The structure of MOSFET includes metal gate, oxide insulating layer and semiconductor substrate. The stability and controllability of this structure make it the core component of digital integrated circuits. In the early 1960s, scientists made improvements to the original MOSFET, using metal as the gate, and successfully developed the MESFET. Then, GaAs FETs were successfully introduced in the late 1960s. With the development semiconductor technology, some high-frequency and high-power applications began to use GaN FETs instead of GaAs FETs. In the 1980s, scientists such as Herbert Kroemer and Tsu-Jae King Liu jointly proposed HEMTs which are a special type of GaAs FET that use a heterostructure. A key feature of HEMTs is the use of two semiconductor materials to enhance electron transport.

Until the beginning of the 21st century, SiC MOSFETs came into everyone's vision and shined in the fields of electric vehicle chargers, solar inverters and high-temperature power management. Until now, SiC MOSFET technology is still being researched to further improve performance, reliability and reduce cost [4]. Since the 21st century, novel FETs such as graphene transistors and two-dimensional material transistors have attracted extensive research interest. These novel materials and devices have unique electronic properties and are expected to change the electronics landscape in the future, for example in the fields of ultra-high frequency communication and quantum computing.

There are four main FET types in modern times, they are Junction Field Effect Transistor (JFET), Metal Oxide Semiconductor Field Effect Transistor (MOSFET), Metal Semiconductor Field Effect Transistor (MESFET), High Electron Mobility Transistor (HEMT). In recent years, with the continuous progress of the electronics industry, field effect transistors are also constantly being reformed and updated, constantly pursuing more practical materials and higher efficiency. In contemporary FET research field, scholars are constantly innovating and optimizing FETs. Such as graphene FET, which uses the two-dimensional material graphene. Due to the large-scale scalability and low-cost characteristics of graphene transistors, also with complete label-free, fast, and high-sensitivity analysis. These features make G-FETs potential for integration into portable instruments and a great advantage in point-of-care biomedical applications [5].

On the basis of two-dimensional material graphene, two-dimensional heterojunctions made of two-dimensional materials like graphene, hexagonal boron nitride, transition metal dihalides, and black phosphorus are gradually making their way into people's fields of vision. It makes up for the limitations of a single two-dimensional material in its application [6]. Specific properties can be obtained by combining different materials into heterojunctions. Such as high mobility, ultra-high switching current ratio and so on. For example, WSe_2 is thermally oxidized to form WSe_2/WO_{3-x} in-plane heterojunction, and its mobility is dozens of times higher than that of WSe_2 [7]. Meanwhile, as far as nanowire FETs are concerned, tiny size, good reproducibility, and ease of electronic integration make CMOS-compatible Si-NW FETs easy to use in system sensors that require a lot of multifunctionality [8]. At the same time, such transistors have been demonstrated to be adaptable potentiometric nanobiosensors for the very sensitive, real-time, and label-free detection of a variety of biomolecules. Finally, for applications that require low power consumption, such as mobile devices, wireless sensors, and wearable devices, researchers are currently working on developing low-power and energy-efficient FETs to extend battery life and reduce energy consumption in data centers, while at the same time Improve usage efficiency.

With the continuous innovation of FET, its application scenarios have also been greatly expanded. Nowadays, there are many fields that need the help of FETs, including integrated circuit, quantum computing, solar cells, biomedicine, and high-frequency communication, etc. For example, in the field of integrated circuits, FETs are the fundamental components of integrated circuits. The continuous development of high-performance FETs has driven the performance improvements of computers, communication equipment and various electronic products. In the field of quantum computing, at its core is the control of qubits. As an electronic control device, FET can be used to control qubits, such as adjusting the coupling between qubits and realizing quantum gate operations [9]. In the field of solar cells, FETs can be used to build power management circuits, including functions such as battery charging, discharge protection, and voltage regulation, to ensure that the output of solar cells is efficiently converted into usable electrical energy. At the same time, it is helpful to track the maximum power point.

The motivation for writing this article is to provide an overview of the two most common types of FETs, the MOSFET and the JFET. In today's era of rapid development of electronic technology, transistors are constantly being improved and innovated. This article aims to introduce and analyze the manufacturing process and application of MOSFET and JFET in recent years and help readers better understand the two modern transistors. The rest part of the paper is as follows. Part 2 will do some basic descriptions to introduce the structure and classification of the main FETs and some features. Part 3 and Part 4 will respectively introduce the process, structure, preparation method and characterization results of MOSFET and JFET in recent years. Part 5 will compare the situation and advantages and disadvantages of the two FETs. Part 6 will introduce the limitations of current research in this field and Part 7 will analyze the outlook for the future. Part 8 will summarize the full text. Some of the references cited are shown at the end of this article.

2. Basic Descriptions

A field effect transistor is an important semiconductor apparatus used to amplify and regulate electric current. There are four main structures and classifications of FETs: Metal Oxide Semiconductor Field Effect Transistor (MOSFET), Junction Field Effect Transistor (JFET), Metal Semiconductor Field Effect Transistor (MESFET), High Electron Mobility Transistor (HEMT). The first is the MOSFET which includes an insulating oxide layer, a semiconductor layer and a metal electrode. It has two main types: N-channel type and P-channel type. NMOS (N-channel MOSFET): In a N-channel MOSFET, electrons flow in the channel. Typically, a positive voltage is given to the gate to make an electron channel in the N-type semiconductor. In a P-channel MOSFET, holes flow in the channel. Typically, a negative voltage is applied to the gate to create a channel for holes in the P-type semiconductor. PMOS usually forms CMOS circuits together with NMOS to realize low power consumption and high-performance logic circuits [10]. In terms of characteristics, it has an extremely high input resistance, meaning it draws little current, making it suitable for low-power electronic circuits. At the same time, MOSFETs are capable of switching at very high speeds, making them widely used in digital circuits. In addition, MOSFETs also have excellent linearity characteristics, making them suitable for analog circuit and amplifier design. Because of their versatility and reliability, MOSFETs are widely used in electronics for various applications such as signal amplification, switching control and power management are one of the key components of modern electronic devices [11]. The SiO_2 can be replaced by other oxides [12].

The second is JFET which consists of a semiconductor material with a junction region of a PN junction that controls the flow of current. There are two main types of JFETs: N-channel and P-channel. N-channel JFET is manufactured using N-type semiconductor material, and electrons flow through a channel of N-type material. P-channel JFET is manufactured using P-type semiconductor material, and holes flow through a channel of P-type material. JFETs are characterized by high input resistance and low noise. They are typically used in low noise amplifier and high input impedance applications [13].

The third is MESFET. Unlike MOSFET and JFET, MESFET uses metal-semiconductor contacts to control current flow. It is commonly used in high frequency and microwave applications. Like MOSFET, MESFET also has N-channel type and P-channel type. MESFET has high-frequency characteristics and high-speed switching speed and is suitable for high-frequency amplifiers and microwave devices. However, their input resistance is relatively low [14].

The last is HEMT which consists of a semiconductor substrate with source and drain metal electrodes and a metal gate on the surface. Semiconductor substrates usually use materials with high electron mobility, such as gallium nitride (GaN) or indium arsenide (InGaAs), for fast electron transport. By controlling the gate voltage, the flow of electrons in the semiconductor can be adjusted to achieve control over the current. Due to its high electron mobility, low noise, fast switching, and high-power output, HEMTs are frequently utilized in the domains of communication, radar, microwave amplifiers, and other devices [15].

3. MOSFET

In the past few decades, there was a trend that engineers were trying to reduce the size of MOSFET. If the smaller size of single MOSFET can be achieved, the whole devices containing millions of MOSFET will significantly decrease. In that case, there will be many benefits like increased responding speed and less cost. However, it is unlikely for traditional MOSFET structure to get smaller continuously due to non-ideal factors caused by quantum effects. In order to satisfy the size demand, a fin field-effect transistor (FinFET) was designed. Compared with the traditional MOSFET structure, it has multiple gates instead of one single gate. The gate material is crossed by several layers of channels, thus forming multiple gates structure, as shown in Fig. 1 [16]. This kind of designs are called FinFET because their source and drain look like fins. The FinFET structure enables devices to enhance smaller leakage current and area, thus leading to the faster switching speed than traditional MOSFET structure.

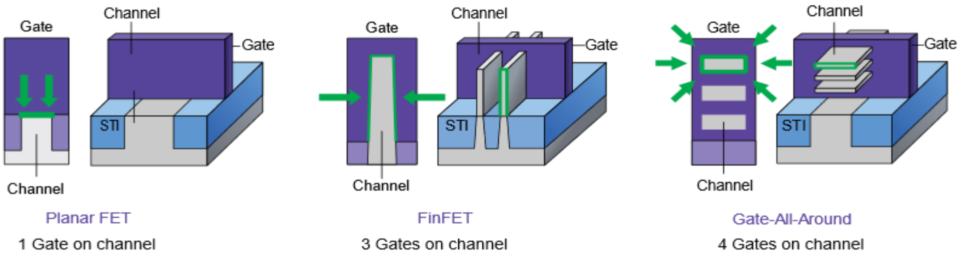

Figure 1. Structure of FinFET

Additionally, scientists are looking for new materials to improve MOSFET performance using Si. In 2011, a company called Cree first put SiC MOSFET into the market. Recently, SiC MOSFET has already substituted for Si MOSFET in many fields like photovoltaic and rail-way applications [17]. Compared with traditional MOSFET made from Si, SiC MOSFET has many advantages. Since SiC atoms has completely different atomic structure from Si atoms, they differ in the properties. The most remarkable difference is that SiC has a much higher critical electric field strength, which means that SiC has a shorter diffusion region and lower diffusion resistance. As a result, the structure is not the same between the SiC MOSFET and Si MOSFET. One of SiC MOSFET structures is shown in Fig. 2. The gate material is surrounded by the oxide. In this design, the on-resistance is reduced, contributing to the lower switching and conductive loss [18].

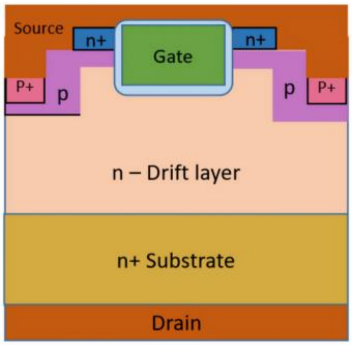

Figure 2. Structure of FinFET

As for the steps for fabrications, firstly, a lightly n-doped layer should be grown by the means of epitaxial growth because its resistance is lower than p-doped epitaxial layer. Then the device is trenched to form the groove face and annealed to restore the atomic structure. On the top of the device, p-doped and heavy p-doped region are formed by Al or N ion implantation in turn, which means heavy p-doped region is above p-doped area. Then n-doped area is formed by the same way with mask to control the implanted area accurately, which works as drain and source of the device. The device is put into thermal oxidation furnace to grow silicon oxide layer, because the oxide growing in this way is denser then that by deposition and is more suitable for high performance gate oxide. Next the electrodes and metal layers are deposited by LPCVD and evaporation to conduct the electrical signals.

There is no doubt that the ideal condition is hard to achieve in real applications. The devices will always be influenced by some non-ideal factors like parasitic capacitance and resistance, which may be caused by the material itself and the metal-insulator-metal structure. These factors will lead to various kinds of energy loss including conduction loss and switching loss. Nowadays, the SiC MOSFET devices have been applied widely in many fields like photovoltaic field. Compared with traditional Si MOSFET, SiC devices have lower conduction and switching loss. One group of testing data is presented in Fig. 3 [19]. Due to this advantage, SiC MOSFET can benefit the whole devices by increasing efficiency and reducing energy loss. As a result, if the fabricating process is mature enough, SiC MOSFET can replace Si MOSFET, especially in high-frequency working condition where the disadvantage of Si devices will be amplified.

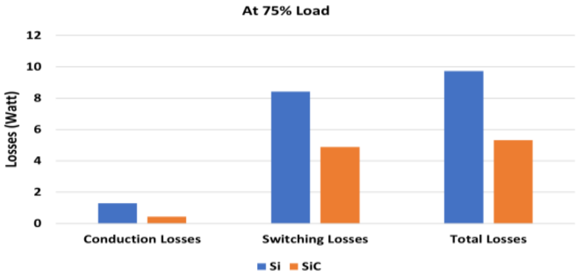

Figure 3. Loss of Si and SiC MOSFET

4. JFET

Compared with MOSFET discussed above, the structure and working principle of JFET is generally simpler. The structure is given in Fig. 4 [20]. It seems that JFET is similar to MOSFET because generally, they are both made from n-doped and p-doped regions and p-n diodes. While the p-n diodes in MOSFET are connected to the source and drain respectively, those in JFET are connected with gate. Unlike MOSFET, JFET does not have any insulation layer and its working principle is to change the channel width by adjusting the gate voltage. JFET also has two main categories: n-type and p-type. For n-type JFET, by applying the voltage between gate and source, the depletion layer will get thicker, thus the channel width will decrease and current will change with it. The current density is related to both gate-source voltage and source drain voltage.

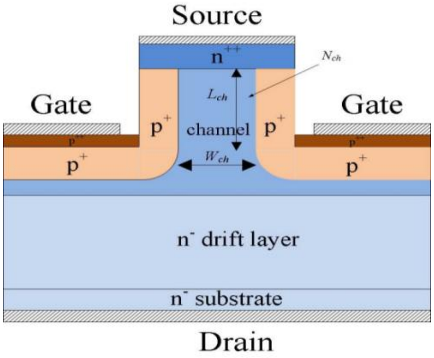

Figure 4. Structure of JFET

As mentioned in the improvement of MOSFET, SiC is found as more competitive than Si in terms of higher critical electrical field and thermal property [21]. Therefore, SiC JFET is also popular these years. Since the structure of JFET is simpler than that of MOSFET due to absence of insulation layer, the fabrication process is also easier. As a result, it is much easier for JFET to generate a high current density. Additionally, SiC JFET devices are widely applied even before SiC MOSFET due to its simplicity.

One kind of SiC JFET structure is shown in Fig. 5 [22]. Initially, similar to SiC MOSFET, epitaxial layer is generated. Then, each type of doping is the most important step among the process because the doping concentration is directly related to the properties of the device. The larger the doping concentration is, the higher saturation current density and lower threshold voltage the device will have. The heavily n-doped area shown in Fig. 5 is implanted by phosphorous instead of nitrogen. And p-doped regions are mostly implanted by aluminum. Next, wafers should be etched to form the proper shapes and generate trenches. In those trenches, other materials like silicon nitride and oxide will be deposited and fill up the empty space. Since there are several levels in the device, these steps may have to be repeated for many times to form different levels. After doping and etching steps, metal layers are deposited to work as electrodes. The device uses Hf and Ti as electrodes because they can stand for higher temperature compared with the most widely used Ni, especially when temperature is higher than 500 degrees Celsius.

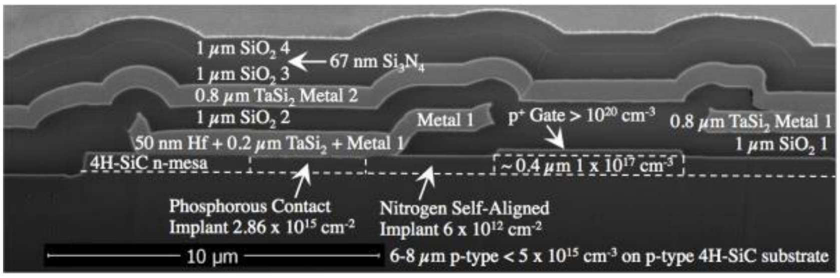

Figure 5. Fabrication structure of JFET

JFET devices have entirely different I-V curves for different types. As illustrated in Fig. 6, the left one is the curve of n-type JFET while the right one is that of p-type JFET [23]. When the thermal condition changes, there is an obvious change in the drain current. The However, the absolute value of the change is not apparent. When the drain voltage increases to about 3v, the drain current does not continue growing with voltage. In other words, both types of JFET can work with a low leakage current [23].

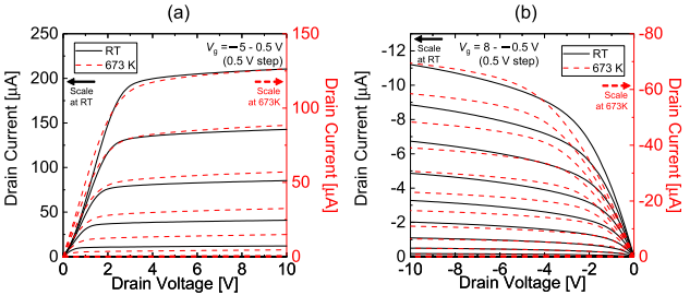

Figure 6. Loss of Si and SiC MOSFET

Additionally, the non-ideal factors may have bad effect on JFET and lead to the energy loss. In the Fig. 7, ‘Conv. SiC JFET’ and ‘Prop. SiC JFET’ both represents for SiC JFET, but with different structure. The former structure is traditional one as shown above in Fig. 3. The latter one is an improved one by adding Schottky contact on both sides of the channel [24]. Although it is obvious that the new design improves the loss significantly, it adds the difficulty to fabricate the device, which is the most competitive property of JFET. As a result, for JFET, it is hard to gain great efficiency as well as simplicity of fabrication.

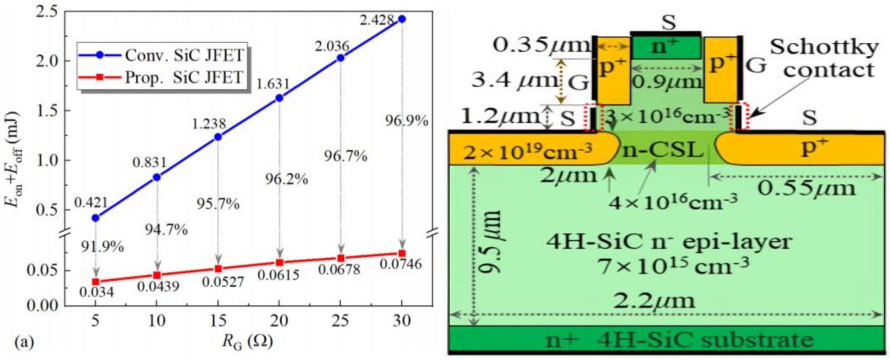

Figure 7. Loss of two kinds of SiC JFET

5. Comparison between SiC MOSFET and SiC JFET

In terms of similarities, both MOSFETs and JFETs are voltage-controlled devices that utilize an electric field to regulate the flow of current. Both transistors operate in three regions: cutoff, saturation, and linear. Additionally, they find wide application in various fields, including amplifiers, switches, and logic circuits. However, there exist several key distinctions between MOSFETs and JFETs. Firstly, their construction differs. MOSFETs consist of a metal gate that is separated from the semiconductor channel by a thin insulating layer of silicon dioxide. On the other hand, JFETs have a PN junction between the source and the drain, which controls the electric field by altering the depletion region.

Regarding the fabrication process, MOSFETs are primarily manufactured using a complementary metal-oxide-semiconductor (CMOS) process, which involves depositing thin layers of materials and creating patterns through photolithography. In contrast, JFETs are typically fabricated using diffusion processes to establish the PN junction and by depositing metal contacts for the source, drain, and gate. The performance characteristics also differ. MOSFETs generally have larger gain, higher input impedance, and lower output impedance compared to JFETs. They also exhibit lower susceptibility to thermal noise. JFETs, although they may have lower gain, offer simpler fabrication and possess inherent voltage-controlled characteristics. The primary obstacle in dealing with power semiconductor devices lies in the need to reduce their switching losses while keeping the switching noises within an acceptable range. In a recent study, it was found that in the same test circuit, the Conventional Gate Drive (CGD) circuit, SiC JFET was found to have much lower switching losses compared to SiC MOSFET using double pulse test (seen from Fig. 8) [25].

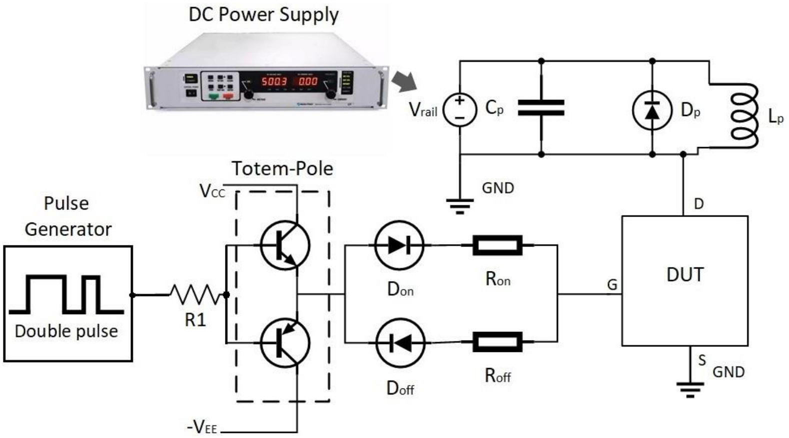

Figure 8. Test circuit for CGD using a double pulse method

However, the assertion that the CGD circuit alone is insufficient for establishing this fact cannot be proven, as the optimization of gate driving using a CGD circuit has not been considered. As a result, they propose the utilization of an Active Gate Drive (AGD) circuit (shown in Fig. 9) in this study, where the switching speed can be dynamically adjusted by altering the external gate resistance. The same conclusion can be drawn in the new circuit.

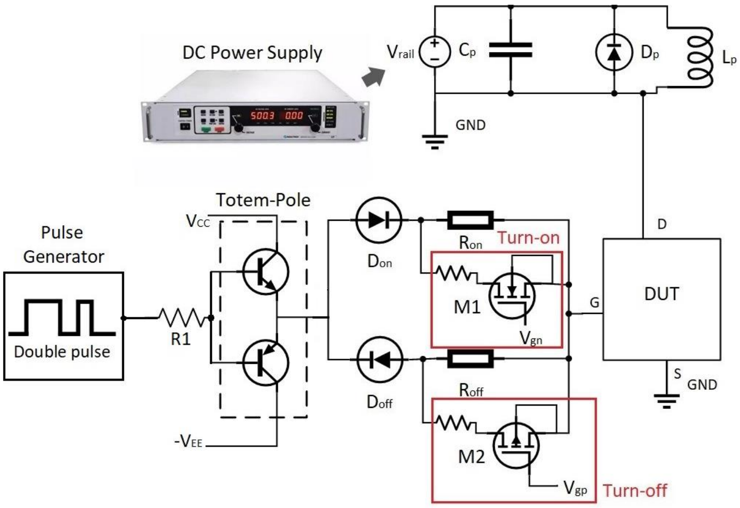

Figure 9. Test circuit for AGD using a similar double pulse method

Another study indicates that the SiC Cascode JFET experienced a source-to-drain short circuit, while the gate remained capable of blocking voltage [26]. In contrast, the SiC Planar and Trench MOSFETs encountered a short circuit when the Gate-Source (VGS) terminal was shorted, but the Drain-Source (VDS) terminals were still able to block voltage. Notably, when the gate voltages of the SiC Planar and Trench MOSFETs were turned off at -5V instead of 0V, the short circuit withstand times increased by 20% for the Planar MOSFET and 9% for the Trench MOSFET. This enhancement can be attributed to the elevated inductance of the negative voltage gate driver, which mitigated the peak short circuit current. Conversely, the short-circuit withstand time of the SiC Cascode JFET did not exhibit any correlation with the VGS turn-off voltage.

6. Current Limitations in MOSFET and JFET Research

Despite the significant advancements in the fabrication and application of MOSFET and JFET, there are still certain limitations that researchers face in these fields. One major limitation in MOSFET research is the challenge of scaling down the transistor dimensions below the nanoscale. This scaling limitation leads to increased leakage current and variability in device performance, affecting the overall efficiency and reliability of MOSFETs. Additionally, MOSFETs encounter issues related to heat dissipation in high-power applications, leading to thermal problems and potential device failure. In the case of JFETs, limitations exist in achieving high-frequency operation due to parasitic capacitances and non-idealities, which restrict their use in certain frequency-sensitive applications.

Overcoming the current limitations in MOSFET and JFET research requires innovative approaches and strategies. To address the scaling limitations in MOSFETs, researchers are exploring new materials and device architectures such as nanowire and nanosheet transistors. These advancements aim to improve control over the channel and reduce leakage current. Additionally, efforts are being made to enhance the thermal management techniques for MOSFETs, including the development of advanced heat dissipation materials and structures. For JFETs, research focuses on minimizing the parasitic capacitances and improving the frequency response by optimizing the device design and materials. Furthermore, investigating alternative channel materials and exploring novel fabrication techniques can help broaden the applications and overcome the limitations of both MOSFETs and JFETs. A study examined a range of simulation studies aimed at comprehending the factors that will ultimately restrict the scaling of devices. The influence of quantum mechanics will become more prominent, but the MOSFET will continue to function as a fundamentally classical device. The challenges encountered by device designers will be familiar in nature, i.e., regulating two-dimensional electrostatics, reducing parasitic effects, managing device-to-device discrepancies, and handling power consumption [27].

7. Future Outlooks for MOSFET and JFET Research

The future of MOSFET and JFET research holds promising opportunities for further technological advancements. In MOSFET research, the ongoing exploration of new materials like 2D materials, such as graphene and transition metal dichalcogenides, presents new avenues for improving device performance and energy efficiency. Moreover, the integration of MOSFETs with emerging technologies, such as neuromorphic computing and quantum computing, holds tremendous potential for next-generation computing systems. In the case of JFETs, continued efforts to optimize the device structures, reduce parasitic effects, and enhance the frequency response will expand the applicability of JFETs in high-frequency and RF applications.

Advancements in device packaging and integration techniques are crucial to harness the full potential of MOSFETs and JFETs. Encouraging collaborations between academia, industry, and government organizations will foster innovation and expedite the translation of research findings into practical applications. Close attention should also be given to the development of reliable and cost-effective manufacturing processes for large-scale production of advanced MOSFETs and JFETs.

Additionally, addressing the environmental impact and sustainability considerations in their fabrication and usage is essential for the future of these devices.

8. Conclusion

In conclusion, the field effect transistor (FET) has a rich development history and various types that have evolved over time. The main types of FET include Junction Field Effect Transistor (JFET), Metal Oxide Semiconductor Field Effect Transistor (MOSFET), Metal Semiconductor Field Effect Transistor (MESFET), and High Electron Mobility Transistor (HEMT). In recent years, research progress in FETs has focused on exploring new materials and optimizing their performance.

MOSFETs, with their insulating oxide layer, semiconductor layer, and metal electrode, have become a key component of digital integrated circuits due to their stability and controllability. SiC MOSFETs, in particular, have gained attention for their superior properties and are being researched for further performance improvements. On the other hand, JFETs, with their simpler structure and voltage-controlled characteristics, have found applications in high-frequency and RF applications. SiC JFETs have also gained popularity for their ease of fabrication and higher current density. In the comparison between SiC MOSFETs and SiC JFETs, MOSFETs have larger gain, higher input impedance, and lower output impedance, while JFETs offer simpler fabrication and voltage-controlled characteristics. Both types face non-ideal factors that may lead to energy loss, but advancements in gate driving, improvements in device structure, and optimization techniques have been explored and show potential for minimizing these limitations.

Overall, the research and development of FETs have paved the way for technological advancements in various fields. The ongoing progress in FET research holds promising opportunities for further advancements, and the integration of FETs with emerging technologies will shape future computing systems. Attention should be given to device packaging, large-scale production, and environmental considerations to ensure the practicality and sustainability of FET-based devices.

Author Contribution

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

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