

Overview of Recent Progress of Semiconductor Power Devices based on Wide Bandgap Materials

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Abstract. Wide bandgap materials, which have shown superior material properties, such as better thermal conductivity and excellent electric performance, have aroused wide concern from scientists and engineers. Currently, research towards semiconductor power devices based on wide bandgap materials has made great achievements. The new developed WBG (wide bandgap) power devices, such as 1200V Direct-Driven SiC JFET power switch and highly reliable GaN MOS HFET displayed better performances and advantages, comparing to traditional Si based power devices. These power devices have been widely used in variety of applications with its successful commercialization, which convincingly proved their reliability and effectiveness. The usage of WBG power devices greatly improved the circuit performance, contributed to the evolve of the new generation electric products. In this paper, we mainly focus on introducing recent progresses and research results of several type of power devices based on WBG materials, including GaN, IGBT, JFET, MOSFET, rectifiers and their SiC counterparts. Their characteristics, performances and relevant applications will be discussed and compared respectively. Then, some deficiency and limits of these devices, as well as solutions of these defects will be illustrated. Finally, future developments and prospects of WBG power devices will be analyzed.

1. Introduction

Semiconductor power device has played an essential role in many applications, such as military applications and microwave communications, where high electric performance was needed. However, with the requirements toward power devices became gradually strict, traditional Si based devices can hardly satisfy these requirements. Generally, high-performance power devices must have high on/off current ratio, high breakdown voltage, fast switching speed, excellent performance under high temperature, low leakage current and many other characteristic that Si devices cannot reach. Thus, scientists and engineers desired devices with better performance and property. Power devices based on Wide bandgap materials, with their intrinsic advantages like wide bandgap (WBG), high breakdown field, high saturation drift velocity, and its high thermal conductivity, makes it a potential next generation of microelectronics. The wide usage of WBG devices will allow higher efficiency of electric energy transformations and considerable improvement in size and robustness of power devices.

SiC and GaN are two of the most promising ones of WBG materials which have the greatest potential to gradually take the place of Si devices and become dominant in high power electronics. In the past few years, the profound and comprehensive researches resulted in prosperous development of SiC and GaN power devices. Based on traditional Si device, some existing technologies that have successfully applied on Si devices were used in SiC and GaN devices. Meanwhile, devices based on WBG materials with new designs and structures



were proposed in succession----diode, IGBT, JFET, MOSFET rectifiers BJT and so on, Currently, some of these new devices, such as GaN lateral transistors and SiC Schottky diodes, has entered into market and competing with their Si counter parts because of their superior properties. However, although SiC and GaN devices offered outstanding performance, many of them are still under developed. For instance, the main leakage current of GaN MOSFETs comes from subthreshold drain current. Although carbon buffer was a potential solution of reducing the leakage current, however, it has many drawbacks, such as decreasing the switching efficiency and increasing device ON-state resistance. In addition, since the study of subthreshold leakage effect was never performed, further study is needed.

This paper was organized into three sections to present recent progresses and developments of semiconductor power devices based on WBG materials. In sections 2 and 3, power devices based on SiC and GaN are introduced respectively with their properties and performance. Their advantages and limits are discussed and compared. In addition, the comparison between WBG power device and Si based devices is also proposed.

2. GaN Power Devices

2.1 GaN CAVET

Depending on the vertical geometry on bulk GaN material, cascoded current aperture vertical electron transistor (CAVET), has been widely used in high power conversion applications. Usually, GaN CAVETs are normally-on devices, same as HEMTs. Thus, techniques transfer HEMTs to normally-off devices can also be applied to CAVETs. A cascoded CAVET approach that operate CAVETs at normally-off states was presented [1]. The cascode in the structure was designed with a low-voltage Si MOSFET. The experimental result showed that the blocking voltage of the CAVET was 280 V with an OFF-state leakage current of $1 \mu\text{A}/\text{cm}^2$ and the on-resistance was $1.5 \Omega \cdot \text{cm}^2$, both are promising characteristics. One of the advantages of GaN CAVETs is the low switching time. This property offers it smaller converter size and higher system efficiency, making it comparable to SiC MOSFET. Owing to CAVET's high electron mobility, both the turn-on and turn-off delay was remarkably reduced. The turn on and turn off switching waveforms showed the turn-on delay time $T_{\text{on-delay}}$ is 2 ns, and the rise time T_r is 16 ns, while the turn-off delay time $T_{\text{off-delay}}$ is 29.5 ns, and the fall time T_f is 18 ns, which is 2 times faster than that of standard commercial SiC MOSFET. Another promising property of GaN CAVETs is the lower switching power losses compared with other devices, such as SiC MOSFET. Switching energy loss of the cascoded CAVET under the $I_D=20 \text{ A}$ is 209 μJ , which is 3 times lower than that of SiC MOSFET. Table I shows the comparison of CREE SiC MOSFET, simulated SiC MOSFET, and simulated cascoded CAVET, suggests that GaN CAVETs have potentials to take the place of SiC MOSFETs that is currently used in power conversion applications.

Table 1. Comparison of simulated CAVET, simulated SiC MOSFET and SiC MOSFET from cree

Test condition	Parameters	Cree SiC MOSFET	Simulated SiC MOSFET	Simulated GaN Cascode CAVET
$V_{DD}=800\text{V}$ $V_{GS}=20\text{V}$ $V_D=20\text{A}$, $R_{G,EX}=2.5\Omega$	$V_{BR}(\text{kV})$	1.2	1.2	1.3
	$R_{ON}(\text{m}\Omega)$	80	80	80
	$T_{\text{off-delay}}(\text{ns})$	40	55	29.5
	$T_{\text{on-delay}}(\text{ns})$	38	25	18
	$T_f(\text{ns})$	13	10	2
	$T_r(\text{ns})$	24	27	16
	$Q_G(\text{nC})$	90.8	157	88
	$E_{\text{off}}(\mu\text{J})$	305	312	57
	$E_{\text{on}}(\mu\text{J})$	305	304	152
	$E_{\text{TOT,SW}}(\mu\text{J})$	610	616	209

2.2 GaN Rectifier

GaN rectifiers can be used in many aspects, especially in ultra-high power electronic devices because of its advantage, such as its switching properties. Rectifiers fabricated on free-standing substrates have a good characteristic of breakdown voltage. Recently, a variety of approaches have been adopted to produce free-standing GaN substrates, since rectifiers fabricated on heteroepitaxial layers on AlO substrates have a bad thermal conductivity with limited epilayer thicknesses. Based on this concern, in order to further increase breakdown voltage, reducing the background doping in the free-standing substrates is a possible solution [2]. At the same time, these rectifiers still show poor thermal characteristics, however, and the reverse breakdown still shows a negative temperature coefficient, indicating that both forward and reverse leakage increasing rapidly with operating temperature. Thus, future studies should focus on reducing surface and bulk defect density.

2.3 GaN power MOSFETs and HFETs

Traditionally, GaN MOSFETs produced on Sapphire substrate have a serious self-heating effect which leads to a negative impact on the device performance. Thus, a high temperature withstanding material in substrate is needed. In [3], a new GaN MOSFET using SiC as substrate was reported. This new GaN MOSFET has a slight temperature rise, as compared to those are made with Si substrate, because SiC have a high thermal conductivity that can ameliorate the self-heating effect. In order to solve the mismatching of lattice between GaN and SiC, an AlN layer as a buffer layer was added. The heterostructure, which was formed as a combination of AlGaIn and GaN, have the ability of high current generation capability. But not like conventional heterostructure, 2DEG is formed in GaN due to the intentional doping. Thus, a certain doping density should be utilized to annihilate the current collapse effect. The result showed that there is a great improvement of output current. Meanwhile, thermal analysis indicated the temperature rise inside is linear since the lattice temperature is more distributed near to the drain region, because electric field and electronic concentrate near this area. Other characteristics, such as trans conductance of the device is $0.058 \text{ S}/\mu\text{m}$, threshold voltage is 0.932 V , OFF current of the device is $8.67 \times 10^{-7} \text{ A}$, all are desirable for enhancement mode operation.

GaN lateral transistors have entered into market for median power applications. But in higher power, vertical GaN device structure is preferred. Although currently many GaN vertical devices have been reported, however, few of them satisfied the requirement of high power requirement. In [4], a large-area in-situ oxide, GaN interlayer-based vertical trench MOSFET was proposed. Its unique advantages make it a potential choice in power conversion applications. During the procession, a 15 minutes UV ozone followed by 5 minutes cleaning hydrofluoric acid (HF) treatment was added after the trench formation. By comparing the transfer characteristics and gate leakage of the fabricated single unit cell OG-FETs with and without the UV ozone/HF treatment, we can suggest that because of the treatment, about 75% of the residual charge was removed. Thus, leakage current was reduced while the threshold voltage was pushed into a positive value.

AlGaIn/GaN heterostructure FETs (HFETs) is the next generation for the RF and high electronic systems. Owing to its specialty, such as high breakdown voltage, low on-resistance, high mobility in the 2-D electron gas (2-DEG) channel and fewer losses, it has attracted much attention for high frequency and high power devices. Like other devices, the conduction losses in the ON-state resistance R_{ON} and the OFF-state breakdown voltage $V_{\text{BR OFF}}$ are the main limitations. The trade-off between current collapse and on-resistance is also ineluctable. In order to solve this problem, Increasing $V_{\text{BR OFF}}$ while maintaining R_{ON} as low as possible is required. In [5], an AlGaIn/GaN HFET with insulating carbon-doped GaN back barrier for high-voltage operation was introduced. It was proved that the trade-off between current collapse and on-resistance is well controlled and balanced by the Carbon back barrier. The barrier reduced the gate reverse bias leakage, suppressed the subthreshold leakage currents below $10^{-7} \text{ A}/\text{mm}$ in OFF-state conditions and enhanced the device breakdown voltage. In [6], a new recessed gate structure towards normally-off high voltage AlGaIn/GaN HFETT was proposed. Using a MIS gate structure and the recessed etching without the off-set region, 2DEG density was reduced remarkably. V_{th} can be achieved at -0.14 V , even to a positive voltage level without increasing on-resistance. Both ROA and leakage current are limited, which is preferred to high electronic systems. In [7], a new HFET structure that a normally on JFET structure was fabricated between the gate and the drain was exploited. The new devices greatly reduced the electric filed intensity of the MOS gate edge. Also, it proved that comparing to the conventional device, I_{D} saturation current during the short circuit condition was reduced by 30%, when they share the same on resistance. Thus, the problem of low short-circuit capability which bothered traditional normally off GaN HMET devices can be solved properly.

Table 2. Influence of mobility on V_{BR} and R_{ON}

Mobility (cm^2/vs)	V_{BR} of VC-VJFET (V)	R_{on} of VC-VJFET ($\text{m}\Omega \cdot \text{cm}^2$)	V_{BR} of LC-VJFET (V)	R_{on} of VC-LJFET ($\text{m}\Omega \cdot \text{cm}^2$)
1100	1240	4.1	1200	1.4
900	1260	5.2	1310	1.7
700	1280	7.0	1400	2.2
500	1300	10.3	1400	3.1

2.4 GaN JFET

Although many GaN devices has entered into market for years, it still lacks a robust gate technology to ensure its normally-off operation. JFET provide a feasible solution for normally-off devices and has been researched for both Si and SiC. In [8], a normally OFF GaN-based vertical JFET using drift diffusion model was proposed, which makes it the first detailed research of GaN-based VJFET. In order to ensure normally- off behavior, the doping density in the aperture was kept around 10^{16} cm^{-3} , which also contributed to 40% of R_{ON} . Thus, it was contradictory if reducing R_{ON} by increasing the Lap or the doping in the aperture without compromising the threshold voltage and normally off state. Meanwhile, in order to achieve a positive VT, Lap should be maintained below $1\mu\text{m}$, which leads to an increased Ron of the device. Aiming to break this severe trade-off between R_{ON} , Lap, VT, and doping density, a LC (lateral channel)-VJFET was proposed. Table II compared V_{BR} and R_{ON} of LC-VJFET and VC-JFET under different mobility, shows that comparing to VC (vertical channel)-VJFET, LC-VJFET has a lower Ron and higher V_{BR} . The relation between R_{ON} and the VT were reduced as well, so lower R_{ON} can be achieved by a thinner and higher doped n-GaN channel.

2.5 GaN IGBT

Comparing to silicon devices, GaN IGBT have many advantages such as higher blocking voltage and power density. However, traditional devices have several limits, such as un-uniform distribution of electric field at the off state, the exacerbation of current collapse and the inherit tensile stress. Consequently, devices that are capable of performing close to theoretical breakdown limits are required. Currently, most of the efforts have been operated for lateral devices. However, as it mentioned above, vertical devices are preferred in high power applications. [9] reported the simulation results of a punch-through vertical GaN IGBT with different drift layer thickness. In order to increase the maximum blocking voltage, an insulated gate structure was adopted to minimize the leakage current originating from gate contact. The result showed that the simulated breakdown voltage is $V_{BD}=600\text{V}$ and $V_{BD}=700\text{V}$ for $12\mu\text{m}$ and $17\mu\text{m}$ drift layer thicknesses, respectively, which is comparable to that of Si IGBT. Meanwhile, a threshold voltage of $V_{th}=3.5\text{V}$ with $12\mu\text{m}$ GaN drift layer thickness was achieved, suggesting that it is a normally-off device. Also, it is necessary to indicate that the current simulations of their device are not complete. More efforts are needed to optimize its fabrication process and physical parameters, such as ion implantation dose and junction depths.

3. SiC Power Devices

3.1 SiC rectifier

The emerging need of devices which are used in geothermal instrumentation, aerospace and other military applications requires scientists to develop high temperature capable devices. In [10], the first commercially available 1200 V rated SiC Schottky rectifiers was proposed and offer superior electrical performance over competing SiC devices, such as MOSFET and JFET when the operating temperature is over 200°C . These high-temperature Schottky (SHT) rectifiers was fabricated at Gene SiC, which enables it block their rated voltage, even at temperatures as high as 300°C . The blocking I-V characteristics shows that this SHT rectifier has the lowest reverse leakage current, comparing to other commercially available SiC rectifiers. When comparing to its nearest SiC competitor, a 20A SHT rectifiers showed a $10\times$ reduction in reverse leakage current at 1200 V and 175°C . In addition, the temperature dependence of the device was reduced. When the temperature rises, the current increase is slight. The switching characteristic is another promising property of SHT rectifiers. These SHT rectifiers have the fastest switching capability and lowest-in-class switching losses among the 1200 V Schottky rectifier class, due to its lowest near-zero bias junction capacitance. The switching current waveforms shows the peak reverse recovery current is lower than 0.5A and keep constant even when the temperature change from 25°C to 205°C . These temperature independent performances renders SHT an ideal choice of high temperature capable devices.

3.2 SiC JFET

For SiC devices, SiC JFET and SiC MOSFET are two of the most commercially mature transistors. The first commercially available SiC JFET entered into market around 2005. Comparing to MOSFET, SiC JFET have many superior advantages, such as higher reliability, smaller on-resistance, lower cost, low output capacitance and low switching losses. Meanwhile, not like MOSFET, SiC JFET was not bothered by the limited channel mobility and the gate oxide reliability issues, which obviously increase the on resistance. Generally, the normally on quasi-vertical JFET with a lateral channel and an inherent body diode have a lower temperature co-efficient of on-resistance, comparing to the normally-off JFET. While it is also possible to realize a normally-off JFET, however, the disadvantage such as high temperature dependence of the on-resistance and the small voltage range brought by the greatly-reduced channel width is unacceptable. However, currently almost all application topologies use normally-off devices and, most of the gate drivers are designed for normally-off devices. Thus, it is unrealistic to simply replace normally-off device by a normally-on switch. In [11], a 1200 V normally-on SiC JFET was introduced as commercially available SiC power switch, which is a potential choice of photovoltaic inverters. In this design, the direct driven JFET solution was used to employ the JFET as a normally-off device. The usage of a second driver for the MOSFET avoided the limitation of a real cascode circuit. At the same time, the normally-off feature of the real cascode was reserved for irregular operation modes. By building a spice model which is based on 2D device simulations in a first stage, a comparison between SiC JFET and High-speed 3 IGBT series was made. The simulation, which is based on a spice model in the first stage, showed that comparing to high-speed 3 IGBT series, the SiC JFET has higher system efficiency. It has been proved that the system employing the SiC JFET switch is capable of increasing the system efficiency over the full load range. The switching waveforms also indicated that the proposed JFET have an excellent switching property. All these performances suggest that it is a good candidate of photovoltaic inverters.

3.3 SiC IGBT

4H SiC is an attractive semiconductor material for high-power devices. Owing to its high breakdown electric field and high stability at high temperature, SiC-IGBT on 4H-SiC carbon face has lower on-resistance, which makes it a promising candidate of high-power components with reduced size and enhanced reliability. Using SiC IGBT, it will be possible to achieve more than 10 kV MOS controlled switching devices with very low on-resistance. A previous report has demonstrated a SiC p-channel IGBT with a blocking voltage (BV) of 10 kV, as well as a PiN diode with 13 kV. However, the device production is still bothered by a series problem. Comparing to that of N channel. The crystal quality of the p⁺⁺ SiC substrate is very poor, thus the micro pipe density and resistivity will be much higher than that of N channel devices. What is more, the channel mobility is relatively low, since it has an ultra-high interface state density. In order to solve these problems, in [12], a new device called flip-type IE-IGBT was proposed. By employing an IEMOSFET a MOSFET structure and a heavily doped epitaxial p⁺⁺ layer as substrate, the device performance was remarkably improved. A 4H-SiC (000-1) carbon face was used, which increase the channel mobility greater than 100 cm²/V·s. One of the most important parameter is JFET width, since as the JFET width increases, the BV and R_{ON} decreases gradually, while V_f is almost independent of width. Thus, to obtain a higher BV, a narrow JFET width between 1.4-3 μm was chosen. The ultrahigh blocking characteristic showed a blocking voltage of 16V and a RonAdiff (differential specific on-resistance) of 11.3 mm cm² at a V_{GE} of +30 V were achieved, both are promising characteristics. In [13], an N channel SiC IGBT based on 4H SiC was reported. High channel mobility of 4H SiC result in an extremely low forward voltage drop. Meanwhile, due to the low collector-gate, gate-emitter capacitance, and superior switching performance was obtained. The switching waveforms shows that the switching time is 27 ns, switching speed is 149 kV/μs at the turn on transient while the switching time is 81ns, switching speed is 49 kV/μs at the turn-off transient. However, due to the fast switching speed with lower gate resistance, the high frequency oscillation during the switching degrade the switching performance seriously. Since the origin of the voltage induction is the high frequency component in the main circuit current flows into gate drive current, thus, a separation of the gate-driving loop from the main circuit was employed to mitigate the oscillation. It was proved that the gate resistances were reduced to 10 Ω for turn-on and 1.1 Ω for turn-off. Due to the low on-resistance, the switching losses was reduced in turn-on (3mJ) and turn-off (3.6mJ) transient, which shows the superior switching performance.

3.4 SiC MOSFET

Owing to the notable properties of SiC material, such as wider bandgap, high Breakdown Field, high Saturation Drift Velocity, and its High Thermal Conductivity, SiC MOSFET has shown prodigious performance and begin to take the place of traditional Si based MOSFET. The Higher breakdown voltage means higher doping density is possible. Thus, SiC MOSFET can be made much thinner.

Larger drift velocity offers SiC MOSFET a higher switching frequency. High thermal conductivity make SiC MOSFET can operate at high temperature without obvious performance degradation. Based on these characteristics, SiC-MOSFET can be made into superior switching devices since it has unique advantages such as lower switching loss, lower ON-resistance, better thermal characteristics. However, these promising characteristics also bring some problems. For example, the fast switching speed of SiC MOSFET brings higher dv/dt , which may lead to higher switching losses. In [14], a new generation of SiC MOSFET with breakthrough Performance from 900 V up to 15 kV was reported. The newly reported device have a better performance, such as low on-state resistance and improved blocking performance, including system efficiency, switching speed, and power density. By using the planar SiC MOS channel structure, the reliability can be maximized, comparing to SiC trench MOSFETs. By comparing the R_{on} and I_{DSS} under different temperature between the newly designed MOSFET, GaN Cascode HEMT and Silicon SJ MOSFET, it showed that the $R_{DS, on}$ of the 900V SiC MOSFET has much less temperature dependence. Because of the lack of tail current, SiC MOSFET has smaller switching losses, comparing to bipolar devices. The experiment showed that the total energy losses at room temperature are about 17 mJ for the 10 kV MOSFET switched at 10 kV, 10 A and about 27.5 mJ for the 15 kV MOSFET switched at 14 kV, 10 A, was achieved. Both are promising properties. As for the frequency, it has been proved that in both the hard and soft switching conditions, the efficiency are over 90%, which have a positive impact on system cost, weight and size.

4. Conclusion

This paper focuses on introducing recent researching results and progresses of wide bandgap semiconductor power devices. With its outstanding properties like wide bandgap and high breakdown field, devices based on WBG materials, mainly GaN and SiC, showed promising performances in many aspects, gradually challenging their Si counterpart which plays a dominant role in market currently.

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