Investigation of Advanced GaN and SiC Semiconductor Materials: Key Characteristics and Diverse Applications

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Abstract. The development of wide band gap (WBD) semiconductor materials has gained enormous attention to, and among all the materials, gallium nitride (GaN) and silicon carbide (SiC) are at heart because of their high-temperature endurance and enormous potential in high voltage uses. This article summarizes both materials' basics and current status, starting from comparatively illustrating their distinctive merits, such as high breakdown voltage and excellent thermal conductivity. Followed up is a critical overview of various facile preparation strategies, and the advantages and disadvantages of the methods are concluded shortly. Finally, the real-world applications of these two materials are presented and analyzed, and both similar and unique uses for GaN and SiC are illustrated. The bright future of both materials is concluded, and this article clarifies the information needed for both materials throughout the progression.

Keywords: Semiconductor, Wide Band Gap, Gallium Nitride (GaN), Silicon Carbide (SiC).

1. Introduction

Semiconductor, a solid substance with conductivity between insulators and conductors, has been focused since its birth as a rectifier (AD-DC converter) in 1874. Transition metals and their combination with other materials are used. Silicon is most widely used in the initial stages of semiconductor developments. Later, the conduction and valence band mechanisms are further investigated, and materials with various band gaps and band structures are discovered. Over the past few decades, wide band gap materials have been paid more attention to, and GaN and SiC-based devices have been thoroughly researched.

GaN is a wide-band semiconductor with a band gap of 3.4 eV [1]. It holds a wurtzite tetrahedral shape that lacks asymmetry on the z-axis, allowing the polarization to be aggregated along the z-axis, which can be employed to increase the gate width per unit area [1, 2]. In the early discoveries related to GaN, it is used as a component of high-efficiency short-wavelength LEDs [1], but the various advantages allow its uses to be further investigated.

SiC is another type of wide-bandgap material. The market has enlarged in the past two decades. The Schottky barrier diodes and MOSFET were invented in 2010 [3]. It has a bandgap of 3.26 eV, almost three times that of silicon. Compared with silicon. Due to the wide gap structure, SiC is also suitable for high-temperature and high-velocity systems, and in this section, some unique advantages will be discovered. SiC is a radiation-hard material with higher displacement energy and larger electron-hole pair generation energy [4]. It holds a tetrahedral shape by covalent bonds and is a polar substance. The advantages of SiC enable it to be applicated in various fields.

In this article, the unique merits of GaN and SiC materials are revealed in various articles, and these materials are compared. The production process and whether the production methods are advanced or not are discussed, with a final discussion of practical applications of both materials. The future of both GaN and SiC is expected to be bright. It is believed that further investigation and research will lead to discoveries of the wide band gap semiconductor materials.

2. The distinctive merits of GaN and SiC materials

2.1 The merits of GaN

2.1.1 Tolerance to high temperature

The highest temperature limit for conventional electronic devices is about 125 Celsius [2], which reduces the scope of application of these electronics; for the electrical systems of aircraft and other aero vehicles, the materials are expected to remain in the solid phase when the temperature is higher than 250°C to make the system less convoluted, therefore reduce the expenses of the electronics since there is no need for cooling systems. According to Varshini's empirical expression, E(T)=E(0)-(αT^2)/(T+β) [5], the band gap energy decreases as the temperature increases. The normal bandgap for Si materials is about 1.11 eV [6]. The great differences between the band gap of GaN and other materials make the high tolerance for the temperature to be one prominent merit of GaN.

Temperature, as the measurement for the average kinetic energy, higher temperature causes the amplitude of vibration of the GaN to be bigger, thus increasing the system's power output. The intrinsic carrier density is one way to measure the conductivity of the material, represented by the equation [2]:

$$ni = \sqrt{Nc \times Nv}e^{\frac{-E}{2KT}} \tag{1}$$

where Nc means the band width of the conduction band, and Nv is the valence band width. When temperature increases and goes beyond the threshold of 300 °C [2], the carrier concentration gets higher than the doping concentration for many materials like silicon, which is undesirable for the high carrier concentration makes the doping meaningless since it is harder for one to control the material using an electric field. But the intrinsic carrier concentration for GaN is lower than the one of Si and other materials and less responsive to the increase in temperature, which makes GaN more satisfactory.

But there may be drawbacks, for the positive correlation between resistance and temperature increases the resistance. Therefore, thermal energy is wasted within the system. Further investigations can be made about how to solve the potential problems [1].

2.1.2 High breakdown voltage

Breakdown voltage, the highest voltage implied on a diode before the exponential increase in leakage current, is an essential measurement for materials[7]. A high breakdown voltage enables the cut-off frequency and current density to be high, which again affects the velocity of the electrons, thus higher the power output of the system. The improvement in breakdown voltage will increase the depletion width, represented by the function [8]:

$$xd = \sqrt{\frac{2\epsilon}{q}\left(\frac{1}{Na} + \frac{1}{Nd}\right)\ (Vb - Va)} \tag{2}$$

which reveals the direct relationship between breakdown voltage and depletion width. A greater depletion width can rectify the reduction of current to control the devices better.

The high critical field of GaN causes the high breakdown voltage. Unlike silicon and related materials that have a critical field of around 3×10^5 V cm^{-1}, GaN's critical field is ten times the one of silicon. Again, this feature is caused by the wide band gap of GaN since the direct proportional relationship between critical field and band gap energy (E_g) [9]. The high breakdown voltage enables GaN to be used in switched circuit uses, which will be explored later in part 4, widens its applications in various areas.

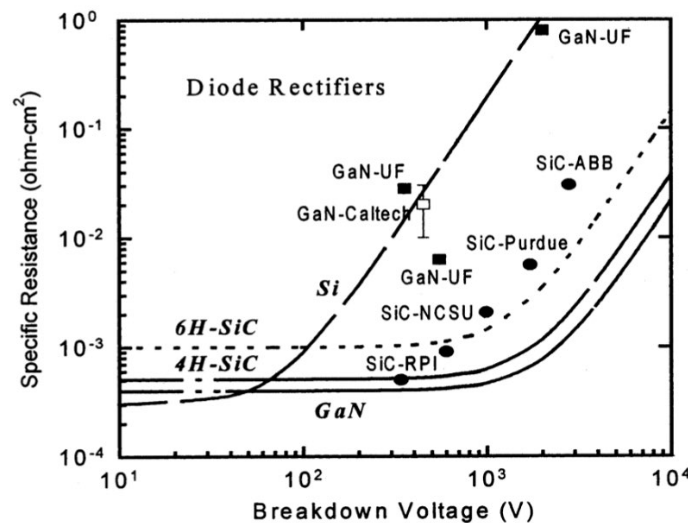


Figure 1. The high breakdown voltage of GaN [10].

2.1.3 High mobility of electrons in the channel

The third merit of GaN is the high mobility of electrons. The Baliga FOM is used to determine the ability to minimize the conduction losses in transmitters with the formula $BFOM = \varepsilon \cdot \mu \cdot E^3$, in which ε is the dielectric permittivity and μ is the electron mobility [11]. The FOM also indicates that the permittivity and electron mobility is proportional to the E_g. Thus, the wide band gap is again the cause for the high mobility.

The attention on the material GaN is mostly on AlGaN-GaN heterostructure devices, the high electron mobility transistors (HEMT) [2]. The multiple epilayers in the HEMT include a 2-dimensional electron gas (2DEG) results from the spontaneous and piezoelectric effect [1]. The difference in polarity drives the electron movement, and the heterojunction, the higher polarization in AlGaN creates the pulse for the electron to move. There is a triangular potential well around the heterojunction, and due to the polarity, a 2DEG is formed generated around the corners of GaN. The 2DEG can help control the devices since the electrons beneath the gas layer are confined to the semiconductor oxide surface [12], thus helping better occupy the energy level. The carrier velocity will increase, thus increasing power output, as said in 2.1.1. The higher frequency caused by electrons' higher mobility makes GaN suitable for various applications.

2.2 The merits of SiC

2.2.1 Excellent Thermal properties

The first merit of SiC is its high thermal conductivity. Unlike silicon, which has a thermal conductivity of merely 2.3 w/cm·k-1, SiC is considered a highly conductive material for having a conductivity of 490 $w \cdot cm \cdot k^{-1}$ [13]. Semiconductors will get heated up when used, and the heat can accelerate the degradation of the devices to reduce their performance [13]. A high thermal conductivity enables the heat to be subtracted and dissipated. The high band gap structure allows SiC to work at high power output as well, and that causes the high thermal conductivity for P/(A)=-k ΔT/Δx [14], where the k represents the conductivity, at the same area and change in temperature, the higher the power, the higher the thermal conductivity. The high thermal conductivity also enables SiC to function in high-temperature situations for good convey of thermal energy[15]. It also makes it suitable for devices that require subtle temperature change, for the high conductivity enlarges the minor changes to amplify the signal.

Furthermore, SiC can bear thermal shocks (rapid temperature changes) due to the low thermal expansion of SiC, which is 4×10^{-6} $°C^{-1}$. Thus, its shape and length are not easily affected by the temperature, making it durable under sharp temperature changes.

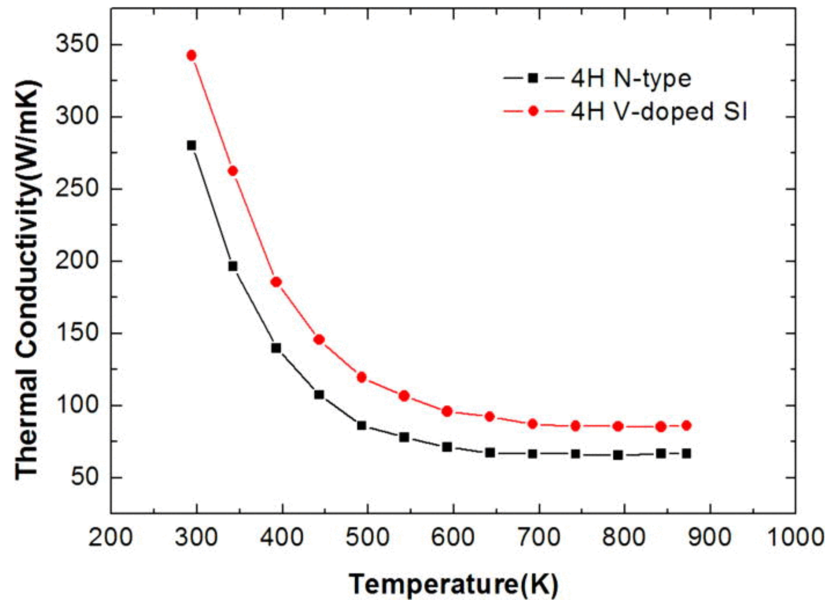


Figure 2. High thermal conductivity of SiC [16].

2.2.2 Low switching loss

Power converters need to be switching at a fast speed and high voltage, but the higher voltage causes a louder switching noise and increases the energy loss [17]. The switching loss is a severe problem when considering the efficiency of one device. The second advantage of SiC is the ease of reducing the switching loss to ensure efficiency in energy transformation. The system of SiC trench MOSFET is widely investigated now, and the most used method to reduce the switching loss is having a P+ shielding layer around the trench [18], which can effectively avoid the gate oxide at the corner of the material to premature breakdown to limit the breakdown voltage [19]. This technology and method are mature and prevailing, but it may limit the number of available electrons in the conducting path from the MOS channel to carriers. This limitation causes higher resistance. Thus, switching loss reduction may cause a higher loss in thermal energy[18]. The other way is to have two trenches, the Rohm's double trench MOSFET (DT-MOS), and the existence of both gate and source trench lowers the on-resistance[18]. But there are limitations such as this causing high capacitance of the devices, and the electric field between trenches may affect the system's functioning so that further research can be done for optimization.

2.3 Comparison between GaN and SiC

Table 1. Comparison of GaN and SiC Resources from [1][2]

Property	Gallium nitride	Silicon carbide
Band gap (eV)	3.4	3.26
Thermal expansion coefficient (10^-6/K)	5.59	2.77
Thermal conductivity (W/cm·K)	1.3	3.8
Electron mobility (cm^2/V s)	1400	950
Electron saturation velocity (10^7 cm/s)	2.4	2
Critical electric field (MV/cm)	3.3	2.5
Wafer size (inches)	2	3

The market of SiC and GaN are similar to complementary sets, for SiC is seldomly used in the major market of GaN--- high-frequency optoelectronics [20]. The composite and different uses of SiC and GaN in various systems will be further discovered in section 4.

The power efficiency of GaN is higher than SiC, for the high electron mobility enables the device to have a smaller depletion area and thus lower the ON-resistance and static power loss. Research has shown that the ON-resistance of GaN is 1/10 of the one of SiC, giving it a higher power efficiency [20].

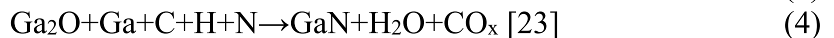
Though SiC and GaN have been paid much attention in the past decade due to their ability to work in high-temperature applications, potential improvements can be made. Due to the high wafer size, SiC materials tend to have large areas but few devices, thus having a low energy integration [2]. The quality of GaN can be improved, and the current limitation of self-heating can be looked at as well [2].

3. Various preparation strategies for GaN and SiC

3.1 Preparation of GaN

The previous methods for preparing GaN have used Gallium and nitrogen gas under high atmospheric pressure (8000-17000 atm) and elevated temperature of 1300-1600 °C, which is unsuitable for volume production [21]. But there are several novel ways of preparing for the GaN. The first is to use a Na Flux, and experiments have shown that after stewing for 96 hours, the ratio of Ga:N is about 1:1, and Na Flux may produce GaN single crystals at a temperature range of 600-800 °C, and a fairly low atmospheric pressure [21]. The other is the evaporation method, in which Ga is deposited on a substrate containing controlled pressure of activated N_2 gas, but the N_2 gas in quartz and the controlled condition of the system is relatively hard to obtain [22]. The first two ways have improved the temperature and pressure, but they still require prohibitive costs and complicated device setup. The third way is by plasma-enhanced chemical vapor deposition (PECVD), which is greener and lowers the cost. The once-used GaN powders are switched to environmentally friendly Ga_2O_3, and the chemicals used, namely carbon and oxygen, are all reducible [23]. The equation is listed below:

$$Ga_2O_3+C \rightarrow Ga_2O+Ga+CO_x \quad (3)$$



$$Ga_2O+Ga+C+H+N \rightarrow GaN+H_2O+CO_x \text{ [23]} \quad (4)$$

These ways all attempted to reduce the cost of producing GaN, but the average cost of preparing GaN is still about ten times that of SiC, making it a major reason for the infrequent use of GaN in a wider field.

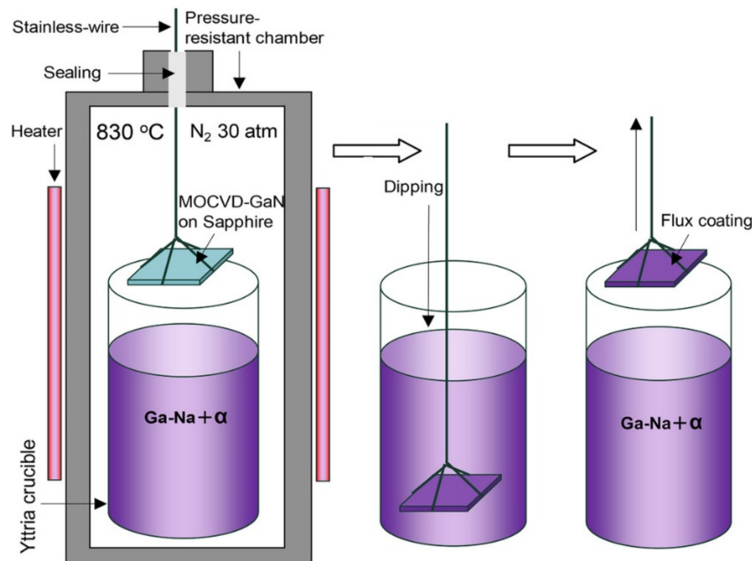


Figure 3. The schematic diagram of the preparation of GaN using flux coating [24].

3.2 Preparation of SiC

The preparation of SiC, on the contrary, is relatively easy and less expensive. The low-temperature fabrications of SiC are matured, such as chemical vapor infiltration (CVI) and reaction sintering (RS). Due to the improvement of advanced Tyranno SA SiC fiber, the high-temperature fabrication of SiC is getting progress. Using Hot Pressing (HP), one can densify the powders of SiC and make the once unstable fibers get crystallize [25]. The tyranny SA fiber has high tensile strength and elasticity

modulus and can maintain the shape without degradation for as high as 1900 °C at a low pressure of around 20 MPa. Thus, it is ideal for high-temperature fabrication [25] with low pollution to the environment. There is another way of fabrication using tetraethyl orthosilicate (TEOS) as the source material to make an insulation layer to prevent the effect of CO_2 generated during SiC oxidation [26]. Research indicates that the interface-state density using TEOS is lower than the one using oxide as a source, and it is verified to be an effective method to fabricate high-quality surfaces of SiC substrates. Though the three are all frequently used, the purity of SiC with the support of TEOS is relatively higher. Thus, the last method is recommended.

The preparation of SiC is maturing and perfecting, while the preparation method of GaN is still at the beginning. Thus, the expenses of fabricating SiC will be significantly lower than that of GaN. But there may be future improvements, and more advanced technologies may change the expenses.

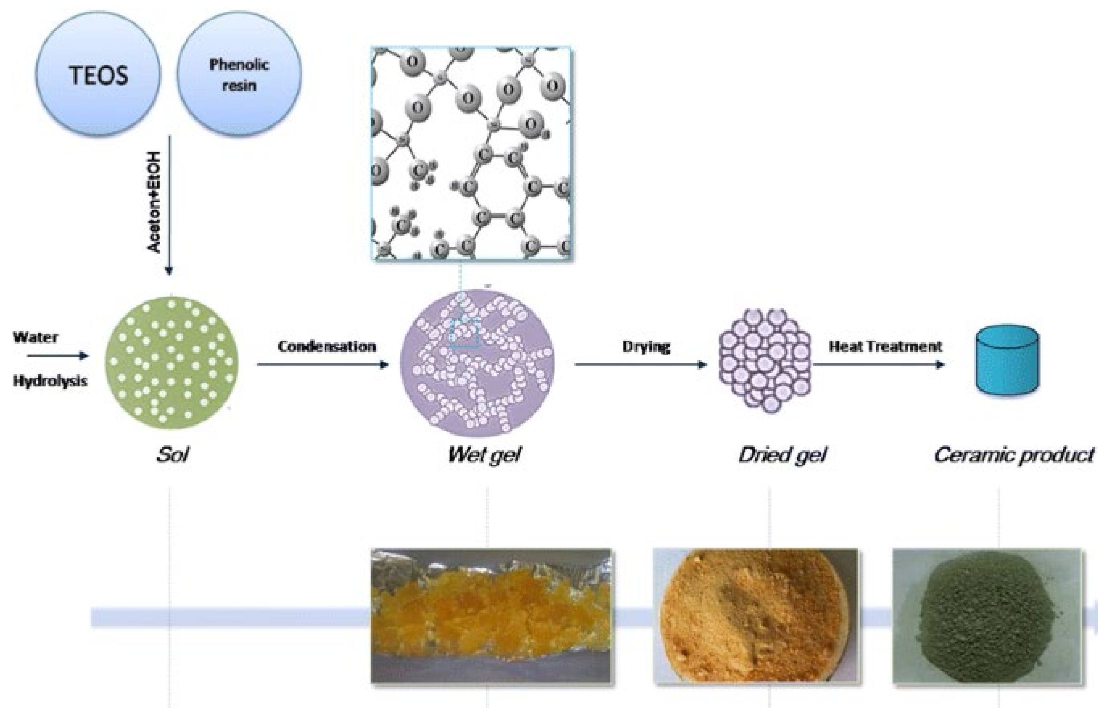


Figure 4. The preparation of SiC using TEOS as support [27].

4. Recent progress in the practical applications

4.1 Similar applications

Comparable properties like wide bandgap and high critical field for SiC and GaN enable them to function in high temperature and high voltage devices. This section will elaborate on the similar uses of GaN and SiC in these two fields.

4.1.1 High temperature uses

Due to its high-temperature endurance and high thermal shock stability, SiC is widely used in fusion technologies such as Fusion Power Reactors (FPR) in the form of Ceramic Matrix Composites (CMCs) [28]. Silicon Carbide matches the priority of FPRs to have a high radiation resistance composite and can keep its features in elevated temperatures and intense irradiations. The long half-life of SiC materials (7.2 X 105 years) makes the fission behaviors activated by the fusion reactor low [28]. The use of SiC in FPR has several advantages, such as it provides safety for the workers and public acceptance of the crowds to the fusion industry, the radiative wastes will be lower for the low activations, and the long half-life makes recycling the materials possible [28].

The high-temperature uses of GaN are in high-temperature sensors in the form of GaN-based MEMS (microelectromechanical systems). Due to the 2DEG, GaN has the potential for monolithic

integration, and the future of single-chip systems developed on GaN technology is possible [29]. Research has shown that the lattice-matched InAlN/GaN devices can operate up to 1000 degrees, enlarging the temperature scope for MEMS. The GaN HEMTs (high electron mobility transistors) can also be used in high-temperature cases, for the electron mobility along with the high switching frequency increases the speed of electron flows in the devices, to make it more precise even in high-temperature uses.

4.1.2 High voltage uses

The high voltage uses of SiC are mainly in ultrahigh voltage SiC diodes using bipolar devices. SiC pin diodes are used in this case, and due to the high carrier density, and high injection efficiency caused by the use of epitaxially-grown pn junction, the diodes can perform accurately and efficiently in high voltage scenarios [30]. But there may also be some future challenges for bipolar devices, for the switching losses are significantly increased compared to unipolar devices. Thus, some SiC technologies are used in HVDC (high voltage direct current) devices to avoid this defect [30].

GaN MOSFETs are used in high voltage devices such as normally-off sapphire substrates; GaN MOSFETs combine the advantage of silicon of low-pressure chemical vapor deposition. The high breakdown voltage of GaN enables the GaN MOSFETs to have a small leakage current around 50 pA for one cycle, increasing its efficiency, and the small resistance enables its use in high-voltage lateral devices, and the future for GaN MOSFETs in high voltage integrated cycle is feasible [31]. But progress can be made on the high On-resistance of GaN, to enable normally-On semiconductor substrates.

4.2 Unique applications

Though there are common application fields, the micro differences in properties and unique advantages of GaN and SiC materials make them have their identical uses.

4.2.1 SiC in aeronautical static inverter

As the air transportation industry evolves and expands, the goal of the future air transportation industry is to increase the efficiency and capacity and lower the emission of CO_2 and the cost; thus, the electrical system has been the top choice for these industries as secondary power sources [32]. This section will discover the use of SiC in the Aeronautical Static Inverter (ASI).

As one of the secondary power sources for aircraft, ASI serves as the major energy supply for AC equipment when the main power supply of the aircraft is DC power and is an emergency power supply for the AC power supply aircraft [32]. Silicon-related devices were used in ASI, but due to the voltage level of about 500 V, the On-resistance of Si is about 1 Ω, whereas the On-resistance of SiC is only 10 mΩ. Due to the direct relationship between resistance and energy loss, theoretically, the loss of SiC is 1% of that of silicon, improving the efficiency drastically. Thus, SiC will be a good choice for ASI and related devices[32].

4.2.2 SiC in MOSFET, JFET

SiC is widely used as a component of various electronic devices such as MOSFETs and JFETs. The feature of each of the two devices will be discovered in this semi-section.

SiC vertical power MOSFET is considered the most desired power device to date, and the normally-off state of the device makes it safe and reduces some potential energy loss. The only flaw is the device's reliability due to the relatively low channel mobility and overly sensitive gate [33]. But the development of SiC MOSFETs in commercial uses has been successful. Cree, Rohm and others have launched 1200v and 1700v SiC MOSFETs in various current values with only exceptionally low resistances. The impressive performances of SiC MOSFET reveal the bright future for this powerful device [32].

As a controllable device with low resistance, high switching speed and high thermal stability, SiC JFET has high reliability for they rely only on pn-junctions. There are two types of JFET, either normally-On or normally-Off. The normally-on JFET may have potential safety problems due to short

circuits, and the normally-off JFET may have a low threshold voltage and be hard to implement in any application. Thus, several major problems should be considered when discovering the optimization of SiC JFET devices[32].

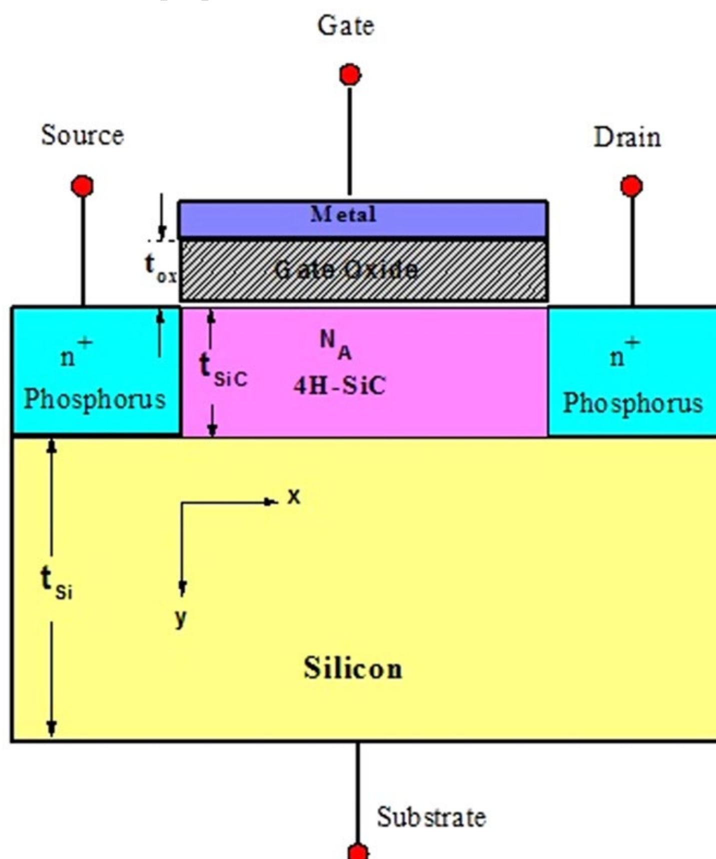


Figure 5. SiC MOSFET structure [34].

4.2.3 GaN in RFPAs

Radio Frequency Power Amplifiers (RFPAs) are often used in electronic warfare (EW), radar and satellite communications and GaN's advantages have made it the best candidate for these devices. Research has shown that GaN has low risk, relatively low development cost, and high efficiency for RFPA, and it offers the highest combination of speed and signal level [35]. There are various commercial RFPA devices at different frequencies, such as QGaN50 (6GHz at 65V), QGaN25 (20GHz at 40V) and QGaN15 (50GHz at 22V). A high-power amplifier requires two functions matching the FET with the system and combining all the signals used in the transistor. GaN can help with both functions. Thus, the power amplifier is a dominant application for GaN now [35].

4.2.4 GaN in DC-DC converters

The use of GaN in aerospace applications is in high conversion ratio DC-DC converters. Due to the higher demand for step-up/down voltage conversion ratio transportation, this field has been increasingly paid attention to. There are several types of High conversion DC-DC converters. This section will discuss the quadratic boost and switched capacitor converter [36].

The quadratic boost converter (QBC) is a two-staged converter that only requires one active switch topology [36]. The efficiency is relatively high, but the whole model assumes that the single switch is ideal for both capacitors [37]. The potential energy losses or less-ideal conditions should be considered in real-life scenarios.

The switched capacitor converter (SCC) is formed by adding additional SC cells to the boost converters. Switched capacitors will get charged and discharged in the switching cycle to help better convert the step-up/down voltages. It has an efficiency of around 89%, higher than the QBCs and is a relatively ideal converter for application.

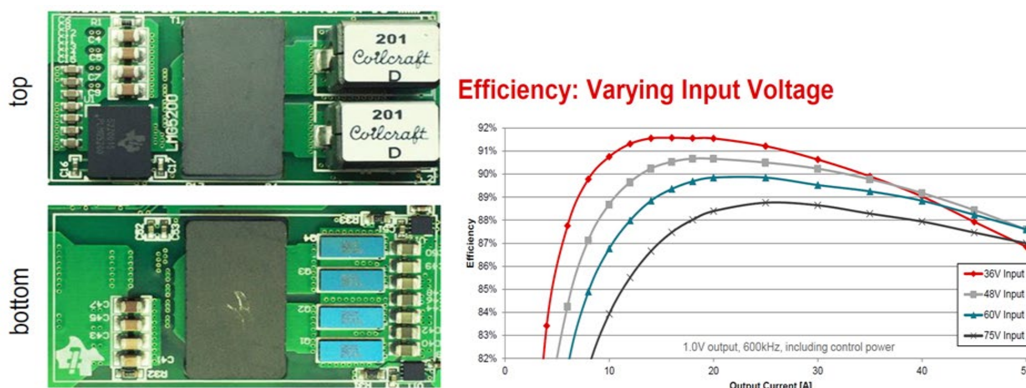


Figure 6. GaN in DC-DC converter with varying input voltage [38].

5. Conclusion

This article comprehensively summarized the advantages of GaN as it can 1) tolerate high temperature; 2) have a high break down voltage; 3) have high mobility of channels, along with the merits of SiC for its 1) high thermal conductivity, low thermal expansion; 2) low switching loss. On a wider scale, the performance and efficiency of GaN-related devices may be slightly better and higher than that of SiC-related devices, but the fabrication methods are expensive and not matured so it may be hard for industrial or commercial use shortly. SiC may be a suitable substitute for Si materials for high temperature and voltage, but the relatively low efficiency and the difficulties of getting high purity materials may forbid its uses. Further research and development can be made to either relatively cut the cost of preparation of GaN devices or improve the efficiency of SiC-related devices.

There may still be improvements for the two materials, the high thermal conductivity of SiC may be further improved by purifying the materials and optimizing their production, and novel methods of producing GaN material in bulks at a lower price can be discovered. The two objects are suitable for relatively high temperature and voltage uses, but there are still aspects for further optimization and completion. The future of these two materials is bright, and one may research the possibility of composite uses of the two materials. Both materials can be used in FET and maybe as an entry point. Discover the composite uses of GaN and SiC can effectively improve the performance of devices at an affordable cost. This may be an aspect of further investigations.

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