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Comparative Study of Typical Wide-Bandgap Power Semiconductor Materials: SiC, GaN and Ga_2O_3

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Abstract. Wide-bandgap semiconductor materials, such as silicon carbide (SiC), gallium nitride (GaN), and gallium oxide (Ga_2O_3), are revolutionizing power electronics technology with their excellent physical properties. In this paper, the similarities and differences among the three materials are systematically compared and analyzed along the dimensions of basic performance, carrier transport mechanism, irradiation response characteristics, and application scenarios. Studies have shown that SiC occupies a dominant position in high-temperature, high-voltage scenarios (e.g., electric vehicle power systems) due to its high thermal conductivity (4.9 W/(cm·K)), and a mature process system. With its high electron mobility (2000 $cm^2/V \cdot s$) and two-dimensional electron gas (2DEG) effect, GaN offers significant advantages for high-frequency, fast charging. Although the thermal conductivity of Ga_2O_3 is low (0.11-0.27 W/(cm·K)), its ultra-wide-bandgap (~4.9 eV) and extremely high Baliga figure of merit (~3444 times that of Si) give it great potential in the field of ultra-high-voltage devices. This paper further analyzes common problems and future directions, such as low defect tolerance, poor gate-oxide interface reliability, and stringent packaging requirements, to provide a reference for selecting and developing wide-bandgap semiconductor power devices.

Keywords: Wide-bandgap Semiconductor, Silicon Carbide, Gallium Nitride, Gallium Oxide, Power Devices, Performance Comparison

1. Introduction

The first generation of semiconductor materials, represented by silicon (Si), has driven the revolution in the microelectronics industry. However, silicon's bandgap, critical breakdown field, and thermal conductivity impose theoretical limits that its devices are now approaching, making it unable to meet the growing demand for high-voltage, high-frequency, and high-temperature applications [1]. Although second-generation GaAs has achieved high-frequency breakthroughs, its limited bandgap and low thermal conductivity remain issues. Third-generation wide-bandgap semiconductors, SiC, GaN, and Ga_2O_3, are leading the power electronics revolution [2, 3]

Development of SiC began in the 1980s. Today, SiC devices can operate at 1700 V and above [4]. GaN was mainly used in LEDs early on, and its transistor potential was not verified until 1991. The discovery of a two-dimensional electron gas (2DEG) in the AlGaN/GaN high-electron-mobility transistor (HEMT) structure has enabled GaN-based devices to exhibit unique advantages in high-

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frequency applications. Ga_2O_3, an ultra-wide-bandgap semiconductor, has attracted significant attention recently. Its bandgap energy is as high as 4.8–4.9 eV, and the theoretical breakdown field strength can reach 8 MV/cm, indicating its great potential in ultra-high voltage devices [5].

However, wide-bandgap semiconductor materials also face many challenges beyond their performance advantages, such as low tolerance to material defects, gate-oxide interface reliability, and specialized packaging requirements, which limit their large-scale application. In addition, existing studies have explored the properties and applications of the three materials, but there remains a lack of comparative research. Therefore, this paper systematically compares the physical mechanisms, performance differences, and applicable scenarios of SiC, GaN, and Ga_2O_3 materials, thereby clarifying the development trajectory of wide-bandgap semiconductor technology and guiding material selection and design optimization for power devices.

2. Basic properties of wide-bandgap semiconductors

2.1. Limitations of silicon-based semiconductors

The bandgap of Si is only 1.12 eV. This leads to a high intrinsic carrier concentration (about 1.5×10^{10} cm^{-3}) and severe leakage current at high temperature, which limits the operating temperature of Si power devices to typically below 150 °C [1]. Because of the low critical breakdown field strength, a high withstand voltage demands a very thick drift layer. This not only increases the device size but also causes a sharp rise in on-resistance. According to the Baliga figure of merit, the power handling capability of silicon is much lower than that of wide-bandgap materials [6]. The thermal conductivity of silicon is 1.5 W/(cm·K), which makes efficient heat dissipation difficult in high power density applications [1]. In addition, Si-based fast recovery diodes (FRDs) show a large reverse recovery charge (Qrr) and a long reverse recovery time (trr), leading to significant switching losses at high frequency [4]. For these reasons, Si can no longer meet the growing demand for high-voltage, high-frequency, and high-temperature operation, and new material systems are needed.

2.2. Core advantages of wide-bandgap semiconductors

Wide-bandgap semiconductors overcome the performance bottleneck of silicon through physical effects that follow directly from their larger bandgap. The intrinsic carrier concentration is set by the bandgap, and the electron–hole pairs produced by intrinsic excitation are far fewer than in silicon at the same temperature. As a result, thermally excited intrinsic carriers cannot cause significant leakage even above 200 °C, and the operating junction temperature can far exceed the 150 °C limit of Si devices. At the same time, for a given voltage rating, the critical breakdown field of wide-bandgap materials is typically one order of magnitude higher than that of silicon. This allows the drift layer to be made much thinner and substantially reduces on-resistance. Many wide-bandgap materials also have higher electron saturation drift velocities, which means lower on-state resistance and faster switching, a combination that is especially important for high-frequency power conversion [1].

As for switching characteristics, wide-bandgap power diodes, especially those made from direct-bandgap GaN and Ga_2O_3, have minority-carrier lifetimes on the nanosecond scale. The charge stored in the drift layer can therefore be removed very quickly, giving near-zero reverse recovery charge and extremely low switching loss, far better than Si FRDs [4, 7]. Thermal conductivity in wide-bandgap semiconductors is not determined only by the bandgap; it also depends on lattice structure

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and phonon transport, and the differences across materials are large. Some wide-bandgap materials have a thermal conductivity that is extremely high, even higher than that of copper, allowing efficient heat removal under high-temperature, high-power conditions.

3. Comparisons of three materials

3.1. Comparison of key performance parameters of three wide-bandgap semiconductor materials

There are significant differences in basic physical parameters among SiC, GaN, and Ga_2O_3, which directly determine their respective device structures and applicable scenarios. Table 1 summarizes the key performance parameters of the three materials. The table shows that SiC has unique advantages in thermal conductivity, GaN has the most prominent electron mobility and saturation velocity, and Ga_2O_3 has an absolute advantage in the Baliga figure of merit due to its breakdown field strength.

Table 1. Comparison of key performance parameters of three wide-bandgap semiconductors [1, 5, 8]

Parameter	SiC	GaN	Ga_2O_3
Band gap (eV)	3.3	3.39	4.8–4.9
Electron mobility (cm^2/V·s)	800–1000	1200–2000	300
Breakdown field strength (MV/cm)	3.5	3.3	8
Saturated drift velocity (10^7 cm/s)	2.0	2.5	1.5–2.0
Thermal conductivity (W/(cm·K))	4.9	2.1	0.11–0.27
Dielectric constant ε_r	9.7	9.0	10
Baliga figure of merit (relative to Si)	340	870	3444
Lattice structure	Hexagonal (wurtzite)	Hexagonal (wurtzite)	Monoclinic

3.2. SiC

Silicon carbide (SiC) is the most commercially mature wide-bandgap semiconductor, and its core advantages are evident across many areas. The thermal conductivity of 4H-SiC is 4.9 W/(cm·K), higher than that of copper (~4.0 W/(cm·K)), and among the highest of all wide-bandgap semiconductors [1]. This enables SiC devices to operate stably at high temperatures and significantly reduces cooling system requirements. Second, the critical breakdown field strength of SiC is about 3.5 MV/cm, which is more than 10 times that of Si, and its Baliga figure of merit is about 340 times that of Si, which means that the on-resistance of SiC devices is much lower than that of Si devices under the same withstand voltage level [1, 6].

In addition, The saturated drift velocity of SiC is 2.0×10^7 cm/s, higher than that of Si, making it suitable for high-frequency power switching. In terms of fabrication, SiC and Si processes are highly compatible, allowing SiC MOSFETs to continue using mature gate dielectric processes. In terms of radiation resistance, SiC itself is not sensitive to heavy-ion irradiation, and the electron energy-loss threshold along the ion track is as high as 37 keV/nm, which is much higher than that of GaN and Ga_2O_3 [9]. Furthermore, it has been demonstrated that vanadium (V) doping can introduce

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deep energy levels into the SiC band gap, compensate for residual N donors and B acceptors, and produce high-resistivity semi-insulating substrates with excellent thermal stability [6].

3.3. GaN

Gallium nitride (GaN) is one of the most outstanding materials among wide-bandgap semiconductors. The electron mobility of GaN can reach 1200–2000 $cm^2/(V·s)$, and high mobility means low on-resistance and fast switching response. A high-concentration, high-mobility 2DEG forms at the AlGaN/GaN heterojunction due to spontaneous and piezoelectric polarization, with an areal density on the order of 10^{13} cm^{-2} and mobility exceeding 2000 $cm^2/(V·s)$ [8].

In terms of switching characteristics, because GaN is a direct-band-gap semiconductor and the minority-carrier lifetime is in the nanosecond range, the reverse recovery charge in its power diode is extremely low (almost zero), and the switching loss is extremely small [4, 7]. The breakdown field strength of GaN is about 3.3 MV/cm, and the theoretical withstand voltage ranges from 650 V to 1200 V [8]. By adjusting the Al composition in AlGaN, the heterojunction characteristics can be continuously tuned, offering additional design flexibility.

3.4. Ga_2O_3

Gallium oxide (Ga_2O_3), especially the β phase, is a representative ultra-wide-bandgap semiconductor. The band gap of β-Ga_2O_3 is as high as 4.8–4.9 eV, and the theoretical breakdown field strength can reach 8 MV/cm, which is much higher than that of SiC (3.5 MV/cm) and GaN (3.3 MV/cm). The Baliga figure of merit of β-Ga_2O_3 is about 3444 times that of Si, 10 times that of SiC, and 4 times that of GaN [5]. Unlike SiC and GaN, β-Ga_2O_3 can be grown by melt methods such as Czochralski (CZ) and edge-defined film-fed growth (EFG). The cost of single-crystal substrates is low, and 6-inch substrates are already available [5]. In terms of optical properties, β-Ga_2O_3 is transparent from the visible to the deep ultraviolet band, with a cut-off wavelength of about 255 nm. N-type doping with Sn, Ta, or Nb effectively controls conductivity, while doping with Co or Mg can introduce deep levels or luminescence centers, showing flexible doping tunability [5].

4. Typical applications

4.1. Typical applications of SiC

4.1.1. Main drive inverter for electric vehicles

The main drive inverter of electric vehicles requires power devices with a voltage rating of at least 1200 V and a current handling capability of hundreds of amperes [4]. The limited installation space and harsh heat-dissipation conditions in the vehicle place high demands on the device's thermal management capability. Commercial GaN cannot yet meet 800 V bus requirements, and the low thermal conductivity of Ga_2O_3 limits its ability to handle hundreds of amperes. SiC is therefore the only feasible wide-bandgap solution for this application. The Tesla Model 3 was the first to use SiC MOSFETs in its inverter. According to reports, the inverter efficiency has increased to over 98%, and the switching loss is about 75% lower than that of Si IGBTs [4]. At the same time, the cooling system's volume is significantly reduced. Currently, BYD, NIO, Ford, and other car companies have followed suit, and SiC has become the standard solution for high-end electric vehicle inverters [4].

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4.1.2. On-board charger and DC-DC converter

On-board chargers (OBC) and DC-DC converters typically operate at voltages between 400 V and 800 V, and they require a high switching frequency (>100 kHz) to achieve miniaturization and high power density. At the same time, they need to operate reliably in a high-temperature, airtight environment. SiC MOSFETs and diodes perform well at this voltage level, and the high thermal conductivity ensures high-temperature reliability. An OBC using SiC Schottky barrier diodes (SBDs) can boost the switching frequency above 100 kHz and triple the power density. Cree's CSD01060 SiC SBD has a reverse recovery charge of only 3.3 nC at 600 V/1 A, and the switching loss is much lower than that of Si FRDs [4].

4.1.3. Irradiation applications

Power systems in nuclear reactors are exposed to high-energy particles such as heavy ions and neutrons, which require devices with high tolerance to single-event effects. Although the SiC material has a high threshold for ion-track formation (37 keV/nm) and good intrinsic radiation resistance, SiC MOSFETs can still experience single-event burnout (SEB) under high-voltage bias [9]. Studies have shown that the SEB threshold voltage of 1200 V SiC MOSFETs under heavy ion irradiation may be as low as 15% of the rated voltage [9, 10]. Therefore, adequate derating and radiation hardening are required to ensure the device's reliability under irradiation.

4.2. Typical applications of GaN

4.2.1. Fast charging adapters and power adapters

Fast-charging adapters need devices switching at hundreds of kHz below 650 V for miniaturization and high power density; SiC is overqualified and costly at this voltage. GaN HEMTs are the choice for this scenario, thanks to their extremely high switching speed (sub-nanosecond) and near-zero reverse recovery charge. Studies have shown that a 65 W fast-charging adapter based on GaN HEMTs has a volume only 1/3 to 1/2 that of a Si-based solution, can reach switching frequencies above 500 kHz, and achieves efficiencies of 94% to 96% [11]. Brands such as Anker, Xiaomi, and OPPO have launched a variety of GaN-based fast-charging products.

4.2.2. Data center power supplies

For 48 V DC-DC converters in data centers, GaN devices provide the fast switching and low on-resistance needed to reach over 98% efficiency and ultra-high power density. SiC has no obvious advantages in the low-voltage field, and Ga_2O_3 is not applicable. GaN devices have significant advantages in this scenario. Data centers operated by companies such as Google and Facebook have adopted GaN power modules, achieving over 98% efficiency and a 40% reduction in volume, effectively lowering operating costs [11].

4.2.3. Wireless charging and RF

Wireless charging systems operating at 6.78 MHz and above require devices to work efficiently at the MHz level. SiC incurs significant losses at such high frequencies, and Ga_2O_3 is not applicable. GaN HEMTs can significantly improve the transmission efficiency in MHz-level wireless charging systems. The efficiency of 6.78 MHz wireless charging systems using GaN devices can reach over

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85%, which is much higher than the 70% of Si-based solutions [11]. In RF power supply applications (such as plasma generators and medical equipment), GaN also demonstrates excellent high-frequency performance.

4.3. Typical applications of Ga_2O_3

4.3.1. Ultra-high voltage power diodes

For ultra-high-voltage diodes beyond 1.7 kV, on-resistance in SiC increases sharply with voltage rating, opening an opportunity for materials with higher breakdown fields. The theoretical breakdown field strength of β-Ga_2O_3 is as high as 8 MV/cm, and the Baliga figure of merit is about 10 times that of SiC and 4 times that of GaN, showing theoretical advantages at this voltage level [5]. The vertical NiO/β-Ga_2O_3 heterojunction diode prepared by Hu et al. achieved an excellent performance of 1.2 kV/2.9 mΩ·cm^2, and exhibited an extremely low peak current (0.36 A at 110 V) in the reverse recovery test, superior to Si FRDs and similar SiC devices [12]. Lu et al. reported that the breakdown voltage of a β-Ga_2O_3 SBD exceeded 2.4 kV, with an on-resistance of only 5.5 mΩ·cm^2 [13].

4.3.2. Solar-blind ultraviolet detectors

Solar-blind ultraviolet detection requires the detector to completely suppress deep ultraviolet light with wavelengths below 280 nm while simultaneously rejecting visible light. The band gaps of SiC and GaN are not suitable for solar-blind detection, and additional filtering is required. The band gap of β-Ga_2O_3 corresponds to a cut-off wavelength of 255 nm, enabling solar-blind detection without complex filtering. Metal-semiconductor-metal (MSM) solar-blind detectors based on β-Ga_2O_3 exhibit an extremely high ultraviolet-to-visible suppression ratio ($>10^4$) and a fast response (on the millisecond scale), with significant application prospects in related fields [5].

4.3.3. GaN-based LED substrates

Substrates for GaN-based LEDs must be lattice-matched to GaN, possess moderate thermal conductivity, and remain cost-controllable. The lattice mismatch between β-Ga_2O_3 and GaN is only about 4.6%, and large-size substrates can be readily produced at low cost by melt growth, making β-Ga_2O_3 a promising substrate material for GaN-based LEDs [4]. The InGaN/GaN multiple quantum well vertical-structure LED fabricated by Muhammed et al. on a (−201) β-Ga_2O_3 substrate demonstrates high luminous efficiency and good heat dissipation, with lower thermal resistance than LEDs on sapphire substrates [14].

5. Discussion

5.1. SiC: cost, interface, and irradiation reliability

The main bottlenecks in SiC power devices are substrate cost, gate-oxide interface defects, and irradiation reliability. Carbon vacancies, silicon vacancies, and Z_1/Z_2-type point defects form carrier capture centers that reduce effective carrier concentration and mobility [15, 16]. The SiO_2/SiC interface state density reaches 10^{12}–10^{13} $eV^{-1}\cdot cm^{-2}$, reducing channel mobility to 1/10–1/30 of the bulk value and causing threshold voltage drift, with reliability problems becoming severe under high-temperature, high-voltage stress [4]. Although SiC has a high latent track threshold (37

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keV/nm), SiC MOSFETs still suffer from single-event burnout (SEB) at high voltage; for 1200 V devices, the SEB threshold can be as low as 15% of the rated voltage [9, 11]. The PVT growth rate is only about 0.3 mm/h, and substrates cost 5–10 times more than silicon [4]. High-frequency switching also imposes tighter requirements on packaging parasitics and electromagnetic compatibility.

Optimizing thermal field uniformity in PVT and developing liquid-phase growth can reduce defect density and substrate cost. New gate dielectrics can improve interface quality and channel mobility. Low-parasitic-inductance packaging, such as chip-scale packages, can address electromagnetic interference from fast switching. Radiation hardening, including buffer-layer design, is also needed for space applications [9].

5.2. GaN: current collapse, voltage level, and p-type doping

The main challenges of GaN devices include dynamic on-resistance degradation, limited voltage ratings, and difficult p-type doping. Surface states and the virtual gate effect in planar AlGaN/GaN HEMTs can increase dynamic on-resistance to 1.7 times the static value under high voltage and frequency, causing significant system loss [17]. Commercial GaN devices remain at voltage ratings around 650 V. Mg p-type doping has an activation efficiency below 10%, limiting the performance of vertical bipolar devices [8]. For GaN under fast heavy ion irradiation, the latent track threshold is about 21–27 keV/nm [9]. In addition, extremely high switching speeds require careful design of the gate-drive loop to account for the packaged parasitic inductances.

Future efforts will focus on vertical device structures to avoid surface-trap-related current collapse and raise voltage ratings. Buffer layer optimization, e.g., C/Fe doping, can control leakage and suppress dynamic on-resistance degradation. Wafer-level packaging and low-parasitic-inductance designs are needed to exploit GaN's high-frequency potential [8].

5.3. Ga_2O_3: thermal conductivity, p-type doping and irradiation damage

The practical application of Ga_2O_3 faces many bottlenecks. First, its thermal conductivity is only 0.11–0.27 W/(cm·K), which is less than one-tenth that of SiC, and the self-heating effect is severe at high power, which is the primary limitation on its high-current applications [5]. Second, the lack of p-type doping makes it impossible to realize bipolar devices, and the research on gate dielectrics related to it is still in its infancy. In terms of irradiation stability, Ga_2O_3 is the most sensitive to fast heavy ions, and its latent track threshold is only about 17 keV/nm, which is far lower than those of SiC and GaN [9]. In addition, cracking and twinning readily occur along the cleavage plane during EFG growth, and preparing large-scale, high-quality substrates remains a challenge [5].

In view of the above bottlenecks, for thermal management, the bonding and integration of a thin substrate with a high-thermal-conductivity heat sink (such as diamond or SiC) can effectively dissipate the device's internal heat [18]. Since p-type doping of Ga_2O_3 is extremely difficult, researchers have turned to exploring heterojunction integration with p-type oxides (such as NiO, Cu_2O, SnO) to achieve bipolar device functions by forming pn junctions [12]. In crystal growth, EFG and Czochralski (CZ) processes are being optimized to reduce cleavage surface cracking and twin defects.

Although each material faces different bottlenecks, solutions can cross-fertilize. SiC's experience in gate-oxide optimization (nitridation annealing, high-k dielectrics) can inform dielectric development for Ga_2O_3 and enhancement-mode GaN [8]. GaN's 2DEG and heterojunction physics can inspire new wide-bandgap heterostructures. Ga_2O_3 heterojunction integration may also help

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improve bipolar devices in SiC and GaN [19]. Low-parasitic packaging developed for SiC and GaN can be adapted for Ga_2O_3 to mitigate thermal and parasitic issues.

6. Conclusion

This paper systematically compares the basic performance, respective advantages, typical applications, and challenges of three wide-bandgap semiconductor power materials: SiC, GaN, and Ga_2O_3. Each of the three materials has unique performance advantages: SiC excels in high thermal conductivity and mature technology; GaN primarily features high electron mobility and the two-dimensional electron gas effect; and Ga_2O_3 possesses an ultra-wide bandgap and an extremely high Baliga figure of merit. In terms of applications, SiC dominates high-temperature and high-voltage applications, such as electric vehicle inverters, while GaN is better suited for high-frequency applications, such as fast charging and LiDAR. Ga_2O_3 has begun to show advantages in ultra-high-voltage diodes and solar-blind detection. However, the three materials still face common challenges, including low defect tolerance, poor interface reliability, and stringent packaging requirements. In the future, challenges remain, such as reducing costs, improving efficiency, and overcoming thermal management and doping bottlenecks.

Limited by experimental conditions, this paper is mainly based on literature research and existing public data for analysis, lacks direct comparative testing of the three material devices under the same process conditions, and focuses primarily on induction and summary, failing to establish a unified theoretical model in depth. In addition, some devices are still in the early stage of research and development, and their reliability and failure mechanisms need to be further verified by experiments. Follow-up research can conduct horizontal comparative experiments to explore new heterostructures (such as SiC/GaN and Ga_2O_3/diamond) that integrate the advantages of various materials and promote the practical application of wide-bandgap semiconductor technology.

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