ADVANCEMENTS AND CHALLENGES IN WIDE BANDGAP SEMICONDUCTOR DEVICES FOR HIGH-EFFICIENCY POWER ELECTRONICS

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Abstract

WBG (Wide Bandgap) devices are an enabling technology that can operate at high switching speeds, is more efficient, can stand higher temperatures, has a higher level of integration, and is lighter and more compact than silicon-based devices. Silicon was running out of steam. WBG has better characteristics for electrically powered equipment, substantial advantages, and inherent material properties. Hence there is increased attention for WBG from both academic and industrial research, and there is also an increased interest in the reliability of SiC (Silicon Carbide) power devices. WBG devices are reviewed from the role of defects and impact on performance. The emphasis of this paper also reviews technical challenges and other issues such as the price of WBG devices being extremely high, SiC MOSFET (Metal Oxide Semiconductor Field Effect Transistors) channel mobility, high dv/dt, electromagnetic interference, EV integration, reflected wave resulting in overvoltage in the load side, noise, and validating the mitigation. Reduction of defects will enable WBG to reach its full potential.

Keywords: **ARWC (Active Reflected Wave Canceller); BPD (Basal Plane Dislocation); CAGR: Compound Annual Growth rate; PVT (Physical Vapour Transport); SiC (Silicon Carbide); TED (Threading Edge Dislocations); WBG (Wide Bandgap)**

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Introduction

Power electronics are a key for power generation, storage, and distribution. The silicon-based semiconductor devices exhibit certain limitations, like operation temperature, switching frequency, blocking voltage capability, low efficiency, low power factor, harmonics, vibration, and commutation issues in motors.

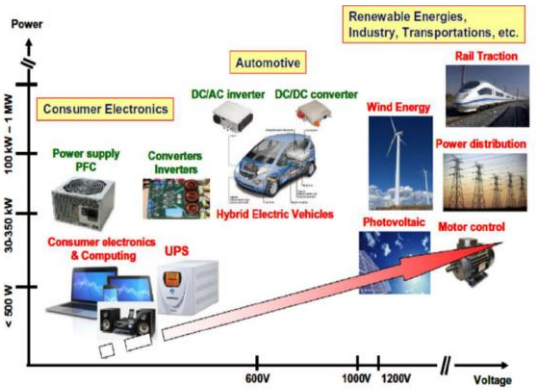

Figure 1. Different applications of WBG devices

In recent years, due to the demand for fossil fuels for power generation, there has been a rapid increase in renewable based power generation. This requires the design of semiconductors for advanced power converters. On the other hand, for a greener environment, the reduction of carbon emissions replaces fossil fuels with renewable energy sources (Subhashini and Kumar, 2017). Researchers believe that WBG devices will stimulate exciting innovations in power electronics (Nakano *et al*., 2019). Figure 1 shows the development of modern technologies such as industrial converters, AC-DC, DC-DC, DC-AC, the Internet of Things (IoT), wireless telecommunication, laser diodes, ship propulsion, smartphones, space technology like land rovers, photovoltaic inverters, low voltage high-speed motors, electric vehicles, and VFD.

In this regard, there is a need for many ranges of power requirements, from W to high MW. Therefore, significant research is going on in the design and development of wide-bandgap semiconductors. The development of reliable power converters, and power electronics devices using WBG is required for efficient operation, high drift velocity, high critical breakdown field, high switching frequency, high durability, higher reliability, low loss, less weight, low harmonics, and high temperature withstand. These advantages of wide band-gap in semiconductors make hot spot research in power electronics devices.

Moore's Law

In 1965, Gordon E. Moore, Intel co-founder, did his observation which is known as Moore's law. Moore's law states that the number of transistors in a microchip doubles every two years, it is expected that the speed and capability of a computer increase in a couple of years with less cost of Microchip devices. Hence the growth of microprocessors is exponential. The production of smartphones, weather forecasting with lifesaving equipment, and all sectors have been improvements in productivity and efficiency due to the reduction of transistor size. However, the physical limits of silicon semiconductors were reached.

Comparison of WBG and Si

At present Si-based power devices cannot be employed when the voltage is higher than 6.5 kV, when the current is higher than 2 kA, and when the temperature is higher than 250°C (Amano *et al*., 1986).

Since Si power devices have a relatively low bandgap and low critical electric field, high voltage will increase the thickness. The large thickness translates to high resistance, low bandwidth will contribute to high intrinsic carrier concentration resulting in leakage of current and conduction losses.

The energy gap width of WBG material is 3.3 eV, which is 3 times that of Si Materials. Therefore, the WBG power semiconductor devices can withstand higher temperatures. The WBG material has a higher breakdown voltage since the critical breakdown field is ten times higher than Si Material. The WBG material has lower conduction loss since the breakdown field is inversely proportional to conduction loss. The electron saturation drift speed of the WBG material is about twice that of Si material, so the WBG device can operate at a higher frequency (Figure 2).

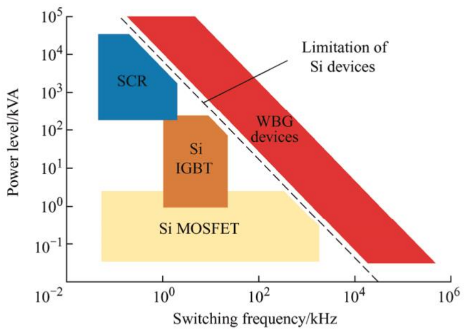

Figure 2. The graph shows the switching frequency difference between Si and SiC devices

Table 1. Shows Physical Properties of Silicon (Si) and Silicon Carbide (4H-SIC)

Electrical Property	Unit	Si	SiC	SiC/Si
Band Gap Energy	eV	1.1	3.26	2.96
Electron Mobility	$cm^2/V.s$	1300	900	0.69
Breakdown Field	V/cm	0.3×10^6	3×10^6	10
Saturation Drift	cm/s	1×10^7	2×10^7	2
Thermal Conductivity	W/cm.K	1.5	3.7	2.46

From the comparison, it can be decided that Si-based devices have limitations in high frequency and high-power conditions (Figure 3).

WBG Material Properties

1. Reduce weight, volume, and life-run cost.
2. The Energy band gap is three times higher, withstanding high temperature
3. The critical breakdown field is ten times higher, which results in reduced thickness, low resistance, and low losses (conduction and leakage loss)
4. Energy Efficiency in industry and consumer Applications.
5. Wide scope of EV & fuel cells.
6. Grid integration.

Why Power Density and Switching Frequency is High in WBG SiC Devices

SiC differ from conventional semiconductors, they have a larger bandgap. the larger distance allows WBG to operate at higher voltage, temperature and frequencies. Figure 4 shows the SiC New model's weight and volume were reduced by 40% of the conventional model.

The bandgap is the energy needed for the electrons to move from the valence band to the conduction band. silicon has a 1.1 ev bandgap, but WBG devices which are made of silicon carbide have a bandgap of 2 ev to 3.3ev (Table 1).

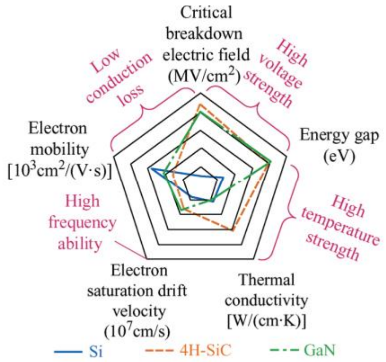

Figure 3. Comparison of different semiconductor material property

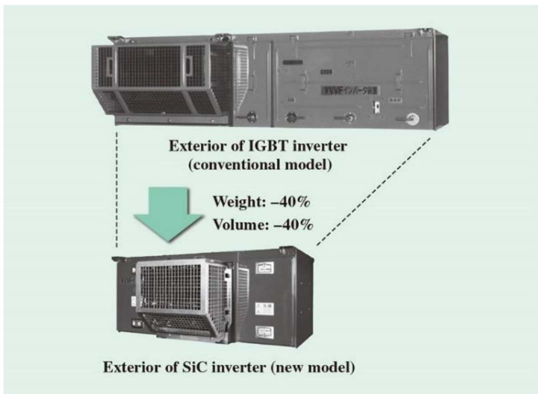

Figure 4. Image shows the difference in size and weight of conventional and new model SiC

Challenges in SiC Devices

The SiC semiconductor industry is demanding new ideas and methods for the development of WBG devices and modules at a reasonable cost (Nakano *et al*., 2019). As we know from the generated energy to the user, the electrical energy undergoes a greater number of conversions. These conversions are inefficient; it is calculated that only 20% of the generated energy reaches the user. The extended faults are BPD (Basal Plane Dislocation), substrate growth, fabrication, stacking, crystal defects, electromagnetic interference, current overshoot, cross-talk effect, negative impact on loads such as motors, and high dv/dt.

Designing the Fabrication of WBG devices is challenging

Undesirable defects in crystal, crystal defects will distort the structure of WBG and cause a downfall in electrical characteristics (Nakano *et al*., 2019). Much effort should be put in by researchers for the reliability of the devices. In fabricating high-voltage devices, the structure change may also cause threading edge dislocations (TED), threading screw displacement due to crystal (TSD), and defects in carbon.

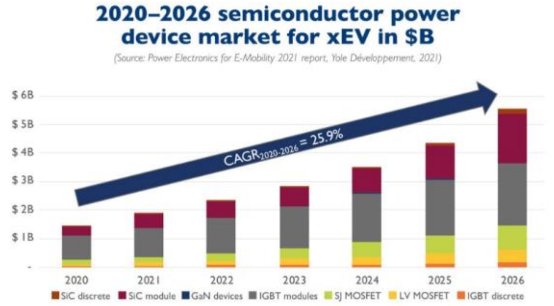

Figure 5. Graph shows the compound annual growth rate

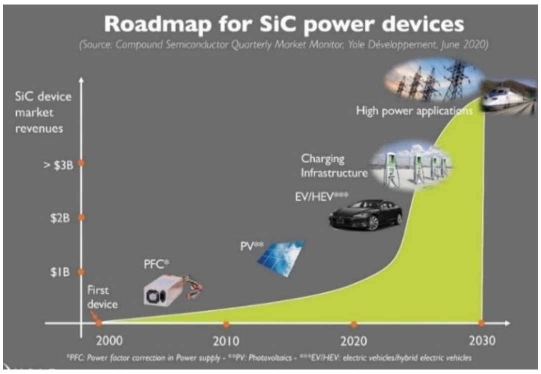

Figure 6. SiC Market price

Price of WBG devices remains extremely high

The material SiC contributes about 40% of the total device cost; the cost is high due to factors like design, fabrication, packaging methods, quality, and availability (Zhang and Li, 2019). Too expensive compared to silicon. Figure 5 shows the annual growth rate for WBG modules.

To make the cost of SiC reasonable, the manufacturing processes can be improved. Most of the manufacturers are making a transition to 150-mm SiC epitaxial wafers (Armstrong *et al.*, 2016). In addition, fabless manufacturing is also under discussion. A fabless company will design and sell semiconductor chips and hardware, but it doesn't manufacture, instead outsources the work to foundries, where skilled labour is plentiful and cheap, which makes production costs low.

Figure 6 Chart and Figure 7 explain the price rise of SiC devices in the market for many applications. The system-on-chip technology uses high voltage and high current and the fabrication of lithography in nano size is challenging.

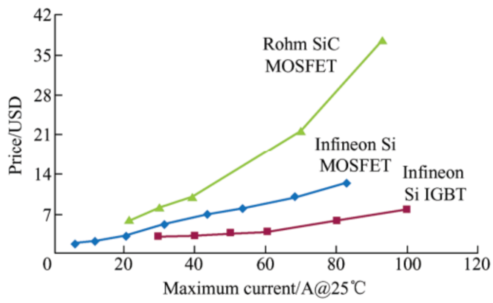

Figure 7. Shows Si and SiC Price difference

High dv/dt

High dv/dt PWM With WBG devices will lead to reflected wave, resulting in overvoltage on the load side, this experiences almost double motor input voltage, which causes insulation failures (Zhang and Li, 2019).

In motor drive control applications, the fast-switching speeds lead to high dv/dt, which impacts overvoltage. Yu Zhang Hui said in Zhang and Li (2019) that the R, L, and C Passive inverter filters are used to reduce dv/dt, but the power loss in the resistors is high, which may fail the working of the resistor. The author proposes ARWC (Active Reflected Wave Canceller) to suppress overvoltage connected between the inverter output and input of the cable in each phase (Figure 8). The bridge generates a controlled small pulse voltage to break the rising and falling edges of the output voltages.

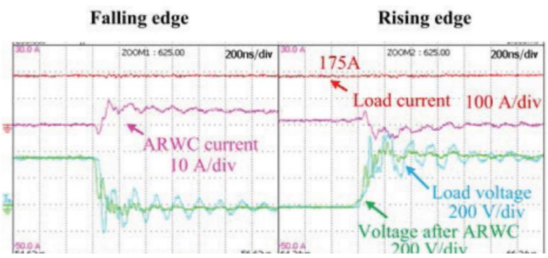

Figure 8. Simulation shows removing of falling, rising edges in the reflected wave

Challenges in WBG integrations

Still, full exploitation of the superior features of WBG is conditional on the development of axillary technology, including designing, cooling, and packaging (Ngwashi and Phung, 2021; Setera and Christou, 2022). The crystal defects may have a severe impact on the performance of WBG commercial applications, including vehicle electrification, utility grid transformation, and renewable energy utilization.

The distribution of BPD in PVT-grown SiC crystals has been investigated using Raman microscopy and has found X-ray topography and

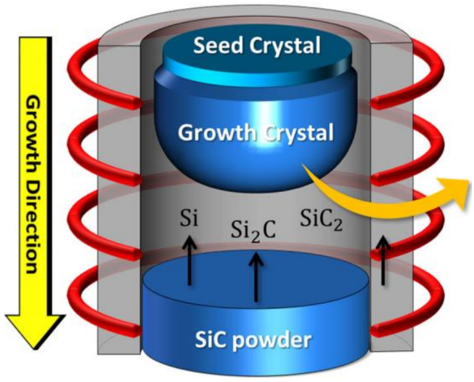

Figure 9. Crystal growth in SiC found large stress

large tensile and stress. This shows characteristics variation in basal plane and crystal growth (Nakano *et al*., 2019). Nakano, Naota has investigated the distribution of BPD, the layers accompanied by large tensile and stress in its upper and lower sides (Figure 9). The PVT Growth method is a dominant method to grow commercially available SiC Crystals. BPD in PVT-grown crystals is currently the most serious impact on devices such as SiC MOSFET, JFET, and bipolar devices.

Device Failure due to High Voltage/High Current Switching

The high-power switching devices experience electrical and thermal stresses, due to high electric fields, magnetic fields, vibration, corrosion, radiation and high current produced during working (Setera, and Christou, 2022). Device failures occur during on state when conducting a high amount of current or when switching high currents and voltages. In one state while conducting a large current, bulk semiconductor material is significantly heated due to joule heating, whereas MOS Junction experiences high charge accumulation and dielectric breakdown. Test should be conducted at various Temperatures to identify the failure parts and causes of failures.

Challenges in SiC Power MOSFET

SiC Power MOSFET is a better energy conversion in electric vehicles and microgrid converters (Ngwashi and Phung, 2021). The main solid-state devices are MOSFET and IGBT used in high-power, high-voltage applications. SiC MOSFET semiconductor devices are capable of operating at higher temperatures, voltages, and frequencies. Since it has an excellent thermal conductivity of 5 W/cmK, Thermal conductivity (k or λ) is a measure of the substance's ability to transfer heat through a material by conduction; it is measured in W/m (Stahbush and Mahadik, 2018). A stacking fault may occur due to the characteristics of BPD. That adversely affects SiC devices by introducing leakage paths and reducing their conductivity. These stacking faults are quantum wells that trap electrons and recombine electrons and holes that degrade the lifetime and reduce the flow of carriers. They also provide a potential barrier that obstructs current flow. The stacking faults that arise from BPD will also affect the leakage of SiC devices by increasing the leakage in the off state.

Thermal electrical Challenges

The goal to improve electrical performance is associated with weight and volume reduction, this may cause thermal constraints (Fouet *et al*., 2022). Wideband gap semiconductors will operate at high frequency, As di/dt increases with frequency, there will be an impact on inductance and surge voltage, To keep low inductance the bus bars are laminated, the laminated bus bar is a good alternative to cables.

Passive components can be found in all electrical systems like power distribution, inverter, and battery. New technology like embedded heat pipe solutions, can help with heat dissipation out of the system.

Conclusions

Conventional silicon power electronics devices can be replaced by WBG semiconductor devices. These characteristics and capabilities lead to energy savings in industry and consumer applications. This should also accelerate the use of electric vehicles and fuel cells. Multiple challenges must be solved to use practical WBG materials in modern electronic devices. Any productive techniques need significant improvement; hence, understanding their failures will lead to the production of highly efficient devices. WBG devices are reviewed at the point of impact of performance and defects; the reduction of defects will enable WBG to reach its full capacity.

This review concentrates on the elements which limit the present-day wide insertion of these technologies in power electronic applications. The present study shows that what is lacking is the fundamental understanding of the role that crystal defects play when WBG semiconductor devices are operating under extreme temperature and voltage environments. For example, it is not clear if certain types of defects are benign, and if they are, then for how long. This basic understanding of the genesis and excited state behaviour of crystal defects is critical to (1) study and quantify the role of specific types of defects on the performance and reliability of WBG high-voltage devices, and (2) devise appropriate material synthesis and device fabrication techniques that yield reduced

Declaration: I hereby declare that the Review entitled “Advancements and Challenges in Wide Bandgap Semiconductor Devices for High-Efficiency Power Electronics” is being submitted by me as my research work, The matter embodied in this article has not been submitted to any other journal for publication and this is prepared purely of academic interest.

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