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Wide Bandgap Transistors Explained With Application Examples

Wide Bandgap Power Electronics: Emerging Converter Technologies and Applications, Isik C. Kizilyalli, Z. John Shen, Thomas M. Jahns, and Daniel W. Cunningham, Editors, Springer, 2025, 712 pages, hardback, ISBN 978-3-031-78630-3.

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"Wide bandgap" (WBG) refers to semiconductors with energy bandgaps wider than silicon alone, such as silicon carbide (SiC) and gallium nitride (GaN). SiC transistors can be either bipolar junction transistors (BJTs) or MOSFETs. Si solid-state electronics theory applies to them except that SiC p-n junctions have a forward voltage of around 1.2 V in contrast to the typical 0.65 to 0.75 V of Si junctions. GaN transistors are high electron mobility transistors (HEMTs) and have junctions like those in Schottky diodes.

The engineering textbook reviewed here briefly introduces readers to the subject of WBG semiconductors and their benefits in power electronics applications before launching into different sections and chapters describing the power circuit topologies and applications in which they may be used. Both the circuits and the applications are typically ones that are enabled by the characteristics of the SiC and GaN devices being used. Hence, they are relatively new in nature, or still in development. Many of the applications are very high in power.

This book is the work of four editors with contributions from many additional sources. The four editors come mainly from academia, but also have industry experience and knowledge of the U.S. government-funded ARPA-E programs to develop WBG devices and applications commercially. Hence the content of the book leans toward the practical both in content and in the design of the book. It contains many color illustrations, which are attractive to read with excellent page layout.

Before discussing the contents of the book further, I'll share my understanding of WBG semiconductors as a point of reference for the readers who may be coming to the topic new.

WBG Transistor Background

In the late 2000s commercialization of power devices began based on gallium nitride (GaN). They are constructed by adjoining two different crystalline materials. GaN joins with AlGaN to form a *heterojunction*, as shown in Fig. 1.

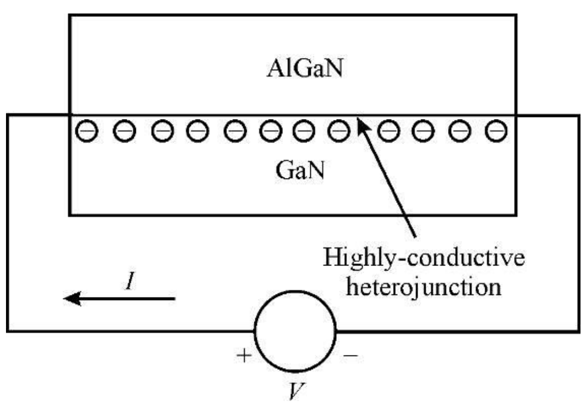

Fig. 1. High electron-mobility junction-like Schottky half-semiconductor, half-metal diode junctions, in which two dissimilar materials are joined. In this case, the junction bandgap voltage is higher, not lower, with free electrons at the junction.

At the metallurgical junction, the crystal interface is under piezoelectric strain and is highly conductive because free electrons result from how the different crystal lattices bond. By 2010, these *high electron mobility transistors* (HEMTs) were commercially available as power MOSFETs.

The HEMT junction is like that of a Schottky diode junction with one side semiconductor joined to a metal. The junction forms a channel along which electrons can flow, as shown in Fig. 1. A gate placed over the AlGaN forms a depletion-HEMT. V_{GS} < 0 V repels electrons from the channel, depleting it and shutting the channel off.

What is more desirable for power circuits is an enhancement-HEMT so that at power-on, switches are in the off state until driven on. One means of controlling channel current is to place a gate in the center and ion-implant a thin layer of fluorine (Fl) in the AlGaN. Fl has a valence of −1 and accepts electrons, depleting the channel under the Fl layer of them and shutting it off. Other methods of making enhancement-mode MOSFETs also exist.

SiC and GaN transistors are the WBG devices of this book. The more strongly bonded GaN has a higher breakdown voltage than silicon and can withstand an electric field up to E_{BR}(GaN) = 3.3 MV/cm; E_{BR}(Si) = 0.23 MV/cm—less by over a decade. The stronger bonding also raises the bandgap voltage at 25°C from V_g(Si) = 1.24 V to V_g(GaN) = 3.39 V. Thermal conductivity of GaN is comparable to Si:

$$\sigma_\theta(\mathrm{Si}) = 1.5\ \mathrm{W/cm\cdot K}\ ;\ \ \sigma_\theta(\mathrm{GaN}) = 1.3\ \mathrm{W/cm\cdot K}$$

The temperature coefficient of channel resistance $TC(r_{on})$ of Si and GaN are both positive but GaN has a lower TC;

$$TC(r_{on}\,,\ \mathrm{Si}) \approx 2\%/\mathrm{K}\ ;\ \ TC(r_{on},\ \mathrm{GaN}) \approx 0.65\%/\mathrm{K}$$

The threshold voltage TCs are quite different;

$$TC(V_{TH}\,,\ \mathrm{Si}) \approx -0.38\%/\mathrm{K}\ ;\ \ TC(V_{TH},\ \mathrm{GaN}) \approx +0.03\%/\mathrm{K}$$

GaN V_{TH} is over a decade more stable with temperature.

HEMTs can conduct in either direction. The reverse-conduction characteristics are not unlike MOSFET body-drain diodes except that diode reverse-recovery charge is miniscule. Unlike in the body-drain diode of a MOSFET, there are no minority carriers to remove. However, the forward voltage drop at the knee of the diode curve is about 2 V, and diode conduction loss is greater.

Silicon carbide SiC is a more strongly bonded crystal than silicon. SiC transistors are not based on a high-mobility heterojunction as are GaN transistors, but are like Si transistors and can be constructed as MOSFETs, BJTs, IGBTs or thyristors. Unlike Si and GaN, SiC has over twice the thermal conductivity; σ_θ(SiC) = 3.8 W/cm·K. Consequently, heat spreads from a SiC die faster and it can dissipate more power at the same junction temperature.

SiC has different crystal configurations; the 4H-SiC room-temperature bandgap voltage is V_g(4H-SiC) = 3.26 V and a breakdown electric field strength of E_{BR}(SiC) = 2.2 MV/cm, about a decade higher than Si. The higher critical or breakdown field strength also reduces r_{on}.

Breakdown voltage is related to the linearly decreasing electric field from the BJT collector junction into the collector n material. A plot of the $E_{BR}(x_D)$ field forms a triangle with voltage as area; x_D is the collector field depth over which the voltage of the field is applied. Breakdown voltage is

$$V_{BR} = \tfrac{1}{2} \cdot E_{BR} \cdot x_D = \tfrac{1}{2} \cdot \frac{\varepsilon \cdot E_{BR}^2}{q_e \cdot N_D}\ ,\ \ x_D = \frac{\varepsilon \cdot E_{BR}}{q_e \cdot N_D}$$

where ε is the permittivity or dielectric constant of SiC n material in the units of F/m, N_D is the donor positive-ion concentration in cm^{-3}, and q_e is the electron charge. Donor atoms supply free electrons which become the majority carriers in n material. The charge density is $q_e \cdot N_D$ in $\mathrm{C/cm^3}$. The V_{BR} numerator units are $(\mathrm{F/cm})\cdot(\mathrm{V^2/cm^2}) = \mathrm{C\cdot V/cm^3}$. The denominator units are $\mathrm{C/cm^3}$, and the resulting expression has the unit of V. In material properties, on-resistance is

$$r_{on} = \frac{4}{\mu_n \cdot A} \cdot \frac{V_{BR}^2}{\varepsilon \cdot E_{BR}^3}$$

where μ_n is electron mobility in $\mathrm{cm^2/V\cdot s}$. $E_{BR}(\mathrm{SiC}) \approx 10 \cdot E_{BR}(\mathrm{Si})$. As r_{on} varies inversely by the cube of E_{BR}, then for the same conductive area and comparable μ_n and ε, r_{on}(SiC) is about 1000 times less than r_{on}(Si). In practice, the advantage is about × 400—a major advancement in reduction of switch conduction loss! As E_{BR} increases for a given V_{BR}, x_D and r_{on} decrease. GaN E_{BR} is × 1.5 that of SiC and has similar advantages.

The advantages of lower r_{on}, near-elimination of diode-reverse-recovery current, and faster switching time of GaN and SiC diodes is offset by the higher forward junction voltage drop. Conduction loss is higher though switching loss is much lower. As both frequency and converter operating voltage increase, switching loss dominates, and v_{on} or V_D is less important.

SiC is less of a departure from Si transistors because its junctions are not the heterojunctions of Schottky Si or GaN. SiC has transistor designs closer to those of Si, including SiC BJTs. They have the advantage of essentially no second breakdown. Although they have base current, BJTs also lack gate overvoltage failures from breakdown of gate oxide in MOSFETs and IGBTs. BJTs are again a power switch alternative in SiC.

A switch performance parameter is the maximum theoretical power that can be switched—the product of $I_{on} \cdot V_{off} = I_{on} \cdot V_{BR}$ where I_{on} is the maximum allowable current when on. GaN and SiC switches have increased this product by a decade or more over Si switches.

Book Contents

With lower on-resistance, higher on-voltage, and higher breakdown voltage, WBG devices are best applied in high-power applications and their use in power electronics appears most frequently in electrical power generation, distribution, and conversion, an overlap of power electronics and *electrical engineering* in its older established meaning. It is not surprising therefore that this book contains 24 chapters in three parts, mainly having to do with high-power power electronics.

Chapter 1 offers an introduction to the subject of WBG devices by the four editing authors, covering somewhat different details than my explanation above. This is followed by part I on “Core Converter Technologies,” which presents 12 examples of particular converters designed and prototyped by multiple authors. These chapters illustrate various high-power circuit topologies such as “matrix,” cascaded multi-level, flying capacitor and switched-capacitor power-transfer circuits.

Control schemes include model predictive and peak current-mode control, and multi-phase circuits appear with the kind of enhanced H-bridge output circuits typically found in inverters. (See the *How2Power Today* battery inverter series noted in the reference for an explained example.) These circuits need to not only be power-efficient but must also minimize the generation of EMI harmonics. Not uncommonly, full-color pictures of prototype circuit-boards are shown along with color waveforms and block diagrams. Both power-transfer and motor-drive inverters are covered, with one chapter on a motor-drive current-source inverter.

Part II has six chapters on “Emerging Applications” and begins with a permanent-magnet synchronous motor (PMSM) drive for a Caterpillar loader. Included applications are a fast electric-vehicle charger, data-center power delivery, and a new application area for power electronics: aircraft propulsion or aviation electrification. Advances in increased power density in motors with WBG drive electronics is leading to the “electric airplane”.

This development might even change the routing of air travel by (p. 361) “taking passengers from large aircraft operating out of hub airports and moving them into smaller regional airports that are more conveniently located” with a reduction in travel times. This was not possible before because of “the unfavorable economics of small propeller aircraft relative to larger jets or single-passenger automobiles.” WBG technology is a critical part of this emergence of electric aircraft. There’s also a secondary benefit to WBG technology in this area as high-power radars can be produced more economically with WBG transistors, also contributing to better routing.

The chapter fills in the argument in engineering detail. Nearly every page has a color photograph in this chapter, of airplanes in whole or part and charger and inverter electronics. The benefit of reduced blood lead (Pb) concentration in one million children living within 6.2 miles of 27 Michigan airports is plotted along with particulate emissions from LAX. The conclusion is obvious.

The charger chapter has some detailed mathematics on harmonics of the modulation scheme of the presented charger. Prevention of circulating currents in the legs of the output circuit is also analyzed along with switching and conduction losses. Inverters do not have simple H-bridge output driver circuits because of the need to minimize EMI from PWMing, and this has led to more-involved topologies with multiple levels and stages of switching and switch sequencing. This chapter offers a tutorial example of what is involved for chargers and inverters.

As an aside, inverters and battery chargers are inverse functions; as I have depicted in Fig. 2.

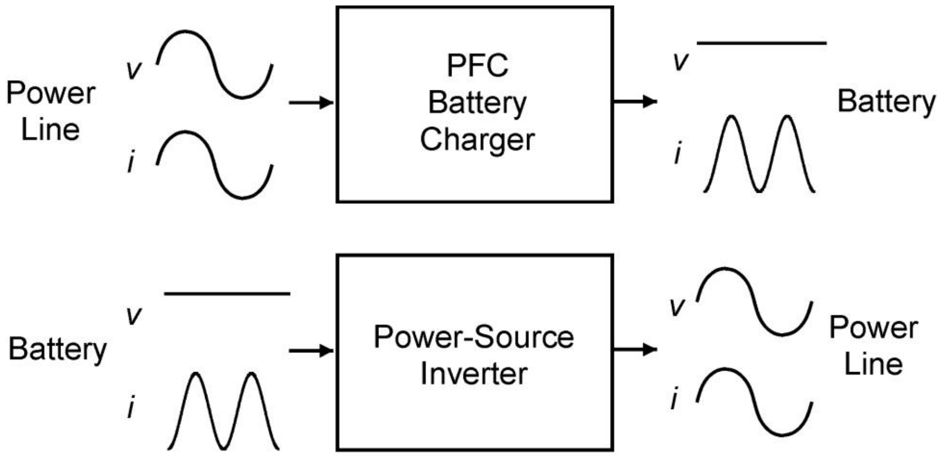

Fig. 2. Powerful battery chargers have power-factor correction (PFC) input stages, making them the inverse function of inverters. Current and voltage waveforms are swapped between input and output.

The chapter on data-center power delivery is more like *electrical* engineering, with site substation and distribution transformer functions in block diagrams, and increasing overlap of electrical and high-power electronics engineering. The rack-level electronics for this design has a 48-V bus as input to converters on "blades". An alternative scheme delivers 380- to 400-V constant voltage to the equipment rack as input to a high-voltage stepdown converter to 48 V followed by a blade-level converter to 12 V.

Part III—the final part of the book—is about "Enabling and Related Technologies". It covers more design examples, of appliance variable-speed motor-drives, EMI considerations in WBG circuits, pulsed-power switching use of SiC where spark gaps and thyratrons are infeasible, and a railgun pulse-forming network. An entire class of pulsed-power systems, including railguns and mass drivers, is based on having a charger—with SEPIC topology, in this case—charge a capacitor bank, then discharge (or "fire") it at high current into a load. Magnetizers and laser flashlamp drivers are other examples.

This design uses a SEPIC circuit for the charger (where they spell out SEPIC as a "single-ended primary-inductor converter" but which I call a SEcondary Polarity-Inverted Ćuk power-transfer circuit). Current-steered PWM-switch converter topologies are inherently inefficient for high-power applications because as much power circulates in their reactive loop as is transferred from input to output port. However, CCM flyback circuits are among the higher performers for transfer efficiency.

The last chapter in part III is related to electric vehicles (EVs) and can be regarded as a kind of tutorial on EV power electronics.

This book is well-designed, has excellent illustrations, and engineering-level content. Compared with other WBG texts I have reviewed previously, this work is more application oriented and up to date. I recommend it as a way to enter the emerging WBG world of power electronics.

Reference

"Designing An Open-Source Power Inverter," a 25-part series of articles by Dennis Feucht.

About The Author

Dennis Feucht has been involved in power electronics for 40 years, designing motor-drives and power converters. He has an instrument background from Tektronix, where he designed test and measurement equipment and did research in Tek Labs. He has lately been working on projects in theoretical magnetics and power converter research.

To read Dennis' reviews of other texts on power supply design, magnetics design and related topics, see How2Power's Power Electronics Book Reviews.

