Latest Book On GaN Power Switches Is Geared Toward Circuit Designers

GaN Power Devices and Applications, Alex Lidow, Ed., Power Conversion Publications, an Efficient Power Conversion company, El Segundo, CA, ISBN 978-0-9966492-2-3, glossy hardback, 278 pages, 2022.

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The topic of this book is identified in the first sentence of chapter one by Alex Lidow, CEO and co-founder of Efficient Power Conversion (EPC): "Gallium nitride (GaN) is a very hard, mechanically stable wide bandgap semiconductor." Lidow, a PhD from Stanford, is one of the leaders in the semiconductor industry and is primary author and editor of the book in which each chapter has a different set of authors. Lidow's name will be familiar to anyone who has been in this business a while.

Similarly, those who have been following the power electronics industry will associate EPC's location, El Segundo, with International Rectifier (now part of Infineon), the company that lead the development of silicon (Si) power MOSFETs. Indeed, Lidow was the former CEO of International Rectifier and closely involved with the development and commercialization of silicon power MOSFETs. Now as the head of EPC, he is leading efforts to supplant silicon power MOSFETs with the new GaN power semiconductors as GaN brings electronics into a new era.

What has hastened the transition from Si to GaN is that GaN crystals can be grown as an epi-layer on Si and also on SiC and sapphire (Al_2O_3). Existing Si production facilities can continue producing large low-cost wafers with GaN. "As with the vacuum tube, silicon power MOSFETs have now reached the end of the road in delivering better performance at a consistently declining cost" (page 2).

Moore's Law, the doubling of transistor density every 18 months, is reaching its end for silicon. GaN transistors with the same power-handling capability are smaller than comparable Si transistors: at 100 V about ×5 and at 200 V, ×16. The smaller chip size results in lower cost.

Furthermore, GaN has not shrunk to its own Moore's Law limits, and present GaN transistors are about 300 times larger than they could be. Integration of power and control circuits is easier with GaN than Si and power systems on a chip are expanding in complexity. As a wide-bandgap semiconductor, GaN also operates up to a destructive limit of 575°C—about three times higher than Si.

This book is a sequel to the 2019 textbook *GaN Transistors for Efficient Power Conversion, Third Edition* published by J. Wiley (the first edition of this book was reviewed in *How2Power Today*—see the reference). As GaN devices have become commercially available, applications for them have increased, and this book is as much about certain applications as about GaN transistors. The name for this kind of transistor is the *high-electron mobility transistor* (*HEMT*).

From a circuit-design standpoint, the HEMT functions much like a high-performance MOSFET. HEMTs are different than Si or SiC MOSFETs in that two different crystalline materials such as GaN and AlGaN are joined, forming a *heterojunction* that is stressed because of the different geometries of the crystals. This causes a layer of free electrons to form at the junction as shown in the figure.

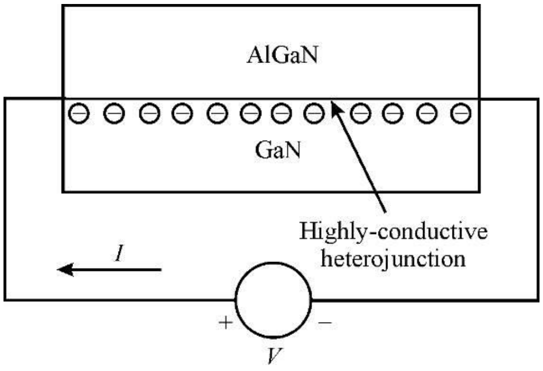

Figure. In a GaN HEMT, a layer of free electrons forms at the heterojunction where GaN and AlGaN materials are joined. This region of the device is highly conductive.

While chapter 1 is introductory (like this review) and gives an overview of HEMTs with an emphasis on performance advantages, theoretical limits, and applications, primarily in power electronics, chapter 2 plunges into "GaN Basics". This is not so much semiconductor physics—few equations appear—as it is the kind of "basics" that a circuit designer wants to know such as HEMT terminal characteristics, especially on-resistance, r_{on}. GaN V_{GS} threshold voltage decreases with increasing temperature by about 8% over 150°C. In contrast, Si MOSFET V_{GSTH} decreases by about 33% over the same range. Gate driver current is reduced by a reduced gate charge.

The EPC2045 (50 V, 16 A) has only 2 nC of charge during the Miller-effect transition region when V_{GS} is constant. EPC HEMTs have been designed to reduce C_{GD} relative to C_{GS} so that dv_{DS}/dt has less effect on v_{GS}, eliminating the spurious fault behavior of a quick rise in drain voltage at shutoff transferring through the C_{GD}-C_{GS} capacitive divider and switching the HEMT back on.

MOSFETs have a body-drain diode that allows reverse conduction, and HEMTs have an equivalent function, but the on-voltage for reverse current depends on gate voltage; negative gate voltage will increase $V_{SD} > 0$ V. Typically it is higher than a Si p-n junction of 2 V to 3 V, characteristic of wide-bandgap semiconductors. However, HEMTs have no reverse-recovery charge Q_{rr} because reverse conduction is not through a p-n junction.

The newer packaging for fast power switches is solder-bump to circuit-board pad under the chip and can be ball-grid array style, with round bumps, or elongated as LGA (land grid array) bumps. By interleaving alternating drain and source lands, inductance is reduced. Board layout and thermal design are addressed in some detail, replete with colored pictures.

Chapter 3 is on "GaN Reliability and Lifetime Projections". This is new territory for many circuit designers in that it presents data on gate-source voltage and temperature effects on time-to-failure. A hot-electron effect similar to how E^{2}PROMs work can deposit deep-state electrons in gate insulator silicon nitride where V_{GSTH} is affected.

However, hot-electron effects on r_{on} have been found to be minimal. Generally, r_{on} rises with time by almost 50% after 10^7 minutes (19 years) of operation, and varies a few percent with switching frequency. Drain voltage also causes an increase in r_{on} over time. SOA curves look like those for other transistors.

One interesting graph shows junction temperature versus time-to-failure for unlimited current. Failure occurs for the devices shown from 500°C to 600°C in about 10 to 20 µs. This gives circuit designers some idea of how long a HEMT can survive without any current protection. These analyses also give circuit designers some idea of voltage, current and time margins for design.

Chapter 4 turns to resistance (dc-dc) converter applications, beginning with dual interleaved PWM-switch CP (buck) power-transfer circuits delivering 300 W out at $V_o = 12$ V and with µC-based current (average or peak not indicated) control. At 25 A, it is 95% efficient with a power loss of 16 W. There is a block-diagram level of control with some frequency-response magnitude and phase plots.

Bidirectional converters are illustrated through an interleaved (two-phase) synchronous buck (CP) and reverse-boost (CA) converter. The power-transfer circuits have a half-bridge switching an inductor in series with a sense resistor with diff-amp to a microcontroller. The outer voltage loop bandwidth is 2 kHz.

One scheme reverses the direction of power flow whenever the voltage drops below a threshold on one of the power ports while the other port has a valid voltage. Another scheme determines power polarity by an external input command. The floating diff-amp performance requirement is loosened by a µC-based average-current control loop driven by a µC-based voltage controller. The current-loop µC control in the forward path is "number of poles, number of zeros" in assembler code.

Multilevel converters continue the chapter, demonstrated by three-level and four-level transfer circuits. The switch sequencing goes through multiple intervals or phases and intermediate capacitors are charged in one phase to be discharged in another, reminiscent of passive voltage-multiplier circuits with capacitors and diodes. The chapter ends with a section on series-L (LLC) resonant converters and includes some coverage of transformer and thermal design.

Chapter 6 continues application of GaN HEMTs to light detection and ranging (Lidar) as does chapter 7 to PMS (permanent-magnet synchronous) motor drives. Chapter 7 has discussion of motor control, drive inverter circuits, and multilevel flying-capacitor drivers.

Then there's the material relating to space applications. Because GaN is a wide-bandgap material, it is less vulnerable to gamma, neutron or ionizing radiation and is advantageously applied to space applications. It is not affected by particles that generate hole-electron pairs, causing the device to momentarily conduct and fail, because in GaN mobile hole-electron pairs cannot be generated.

Gamma rays are energetic and can knock an electron out of the gate oxide of a Si MOSFET, leaving a positive "trap". With enough of these, the channel is biased on and no longer is an enhancement-mode device. In contrast, HEMTs are impervious to gamma radiation; AlGaN does not accumulate charge when exposed to gamma radiation. The third kind of radiation, of neutrons, cause lattice defects. In GaN damage is minimized by the strong bonding between Ga and N. GaN bond energy is significantly higher than that between Si atoms and is comparable to SiC.

The eighth and final chapter is a short preview of GaN integrated circuits. It is followed by the Appendix A glossary, Appendix B EPC evaluation kits' summary of GaN HEMT-based circuit-boards, and Appendix C list of contributors to the book with biographical summaries and color pictures of each, and a six-page index.

My takeaway from this book is that it quickly updates the reader on the current state-of-the-art in power switches for power electronics applications. It is not deep into semiconductor theory and is oriented to appeal to circuit designers. *GaN Power Devices and Applications* is a great way to "come up to speed" on the ongoing advancement in recent years in power switches.

Reference

"Book Puts Engineers On Path To Designing With eGaN Transistors," review of *GaN Transistors for Efficient Power Conversion, First Edition*, How2Power Today, June 2012.

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.