ISSUE: March 2013

Vertical Devices In Bulk GaN Drive Diode Performance To Near-Theoretical Limits

by Isik C. Kizilyalli, Andrew Edwards, David Bour, Hemal Shah, Hui Nie, and Don Disney, Avogy, San Jose, Calif.

High-efficiency power semiconductor devices are the key to improving the efficiency of power electronic systems. For the last three decades, silicon (Si) power devices (MOSFETS, IGBTs, and diodes) have dominated the power device market. During this time there have been tremendous improvements in silicon power device performance. However, these devices are now approaching the physical limits of silicon. Alternative materials, such as silicon carbide (SiC) and gallium nitride (GaN) are enabling a new generation of power devices that can far exceed the performance of silicon-based devices, which will allow continued improvement of the efficiency of power electronics.

SiC diodes have already been commercialized and they are increasing market share in applications that demand the higher efficiency. However, there is also great interest in developing GaN-based power devices because the fundamental material-based figure of merit (FOM) of GaN is at least five times better than SiC and nearly 1000 times that of Si. This is because the power device figure of merit for a majority-carrier device is proportional to the product of carrier mobility with the critical electric field to the power of three ($\mu_n E_c^3$), where E_c is the field at which avalanche breakdown occurs. The critical electric field is mostly determined by the bandgap of the semiconductor and hence the recent emergence of wide-bandgap semiconductors for use in power electronics.

The implications of a larger figure of merit are profound; increased temperature of operation, reduced device area and capacitance, reduced losses during switching, conduction, and off-state summarized in Table 1 for Si, SiC, and GaN.

Table 1. Material parameters and device performance implications.

Property/Material	Silicon	SiC	GaN
Bandgap	1.1 eV	3.3 eV	3.4 eV
Max. electric field	0.3 MV/cm	2.0 MV/cm	3.7 MV/cm
Power device FOM	1	675	3000
Max temperature	150°C	>250°C	>250°C
Capacitance	-	+	++
Off-state loss	++	++	++
On-state loss	-	+	++
Switching loss	-	+	++

In the following discussion, we explain how full advantage of the material properties of GaN is taken by fabricating vertical diodes on low-defect-density bulk GaN substrates. The 600-V to 1700-V rated devices described in this article demonstrate performance near theoretical limits as predicted by the GaN material properties. Measurements reveal robust avalanche breakdown (demonstrated for the first time for a GaN device), which is critical in an inductive switching environment. The performance of these devices in boost and half-bridge topologies is compared to high-performance Si diodes. High-temperature-reverse-bias data establishes the technology’s long-term reliability.

Device Design And Fabrication

Schematic cross-sectional diagrams of vertical GaN Schottky-barrier diodes (SBDs) and pn diodes are shown in Fig. 1. The fabrication of these diodes started with 2-inch bulk GaN substrates and GaN layers epitaxially grown by metal organic chemical vapor deposition (MOCVD). Plan-view cathode-luminescence (CL) imaging reveals that the threading dislocation density in the films grown over bulk GaN substrates is 10^4 to 10^7 cm^{-2}, or at least two orders of magnitude lower than for GaN films grown in the conventional manner on sapphire, silicon, or SiC substrates.

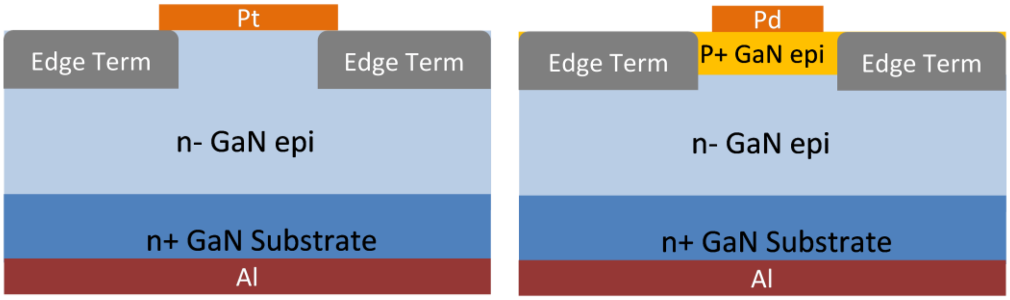

Fig. 1. Schematic cross sections of vertical GaN Schottky diode and pn diode.

The n-type drift-layer layer doping was in the range of 1 to 3 x 10^{16} cm^{-3} and thicknesses were in the range of 6 to 18 µm. These two parameters were optimized to determine the breakdown voltage and the specific on-resistance of the diode. SBDs were fabricated by the deposition and patterning of platinum (Pt) or palladium (Pd) on the GaN epitaxial layer. Pn diodes were fabricated by in-situ growth of a magnesium (Mg)-doped p^+ GaN epitaxial layer on top of the n-type GaN epitaxial drift region followed by deposition and patterning of Pd or Pt to contact the p-type GaN. The p-type GaN has a hole concentration of 5 x 10^{17} cm^{-3} and a hole mobility of 11 cm^2/V-sec at 25°C as measured by Hall effect.

A proprietary edge-termination design was employed to terminate the devices and realize breakdown voltages approaching 85% of theoretical parallel-plane junction breakdown. Backside contacts were formed by evaporating a multi-layer metal stack including aluminum onto the back surface of the n-type GaN substrate.

Fig. 2 shows the measured I-V characteristics of Avogy's vertical GaN diodes. The left-hand graph shows the reverse blocking of pn diodes designed for breakdown voltage (BV) ratings of 600 V, 1200 V, and 1700 V. Up to 10 A of pulsed forward I-V for the 600-V SBD and 1200-V pn diodes is demonstrated.

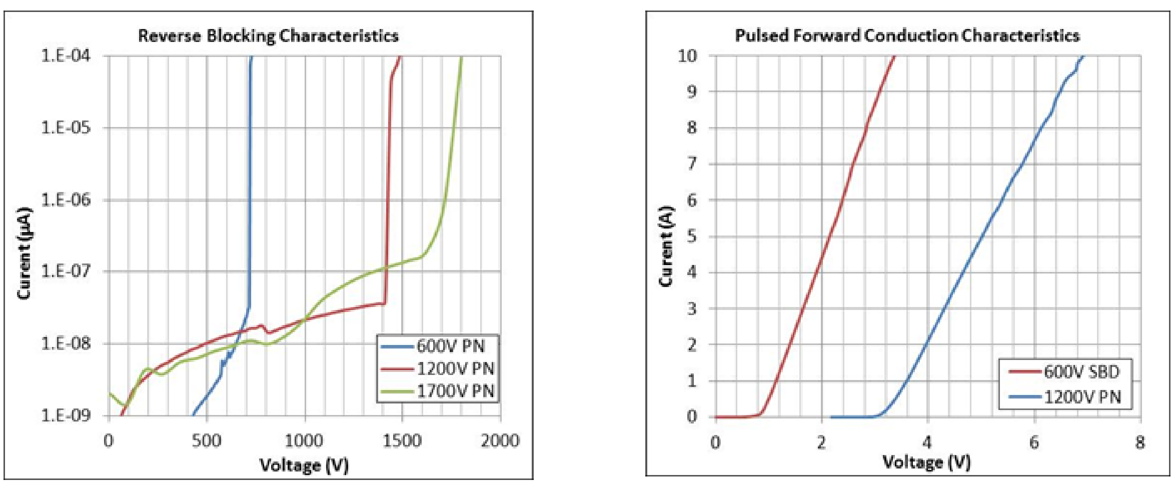

Fig. 2. Measured I-V characteristics of GaN-on-GaN Schottky barrier diodes and pn diodes.

Fig. 3 shows the previously described power device FOM for Si, SiC, and GaN materials. These curves show how the on-state performance and off-state performance are governed by the physical properties of the semiconductor material. The fundamental limits for the drift-region resistance of unipolar devices fabricated in SiC and GaN are shown by solid lines.

Extracted values of specific on-resistance and breakdown voltage from the fabricated diodes described here are shown as solid green dots. Also shown are the published results from vertical SiC power devices. Note that commercial SiC devices are already approaching the theoretical limit for this material system.[1-4] Published results from lateral GaN power devices fabricated on SiC or silicon substrates are also included in the figure.

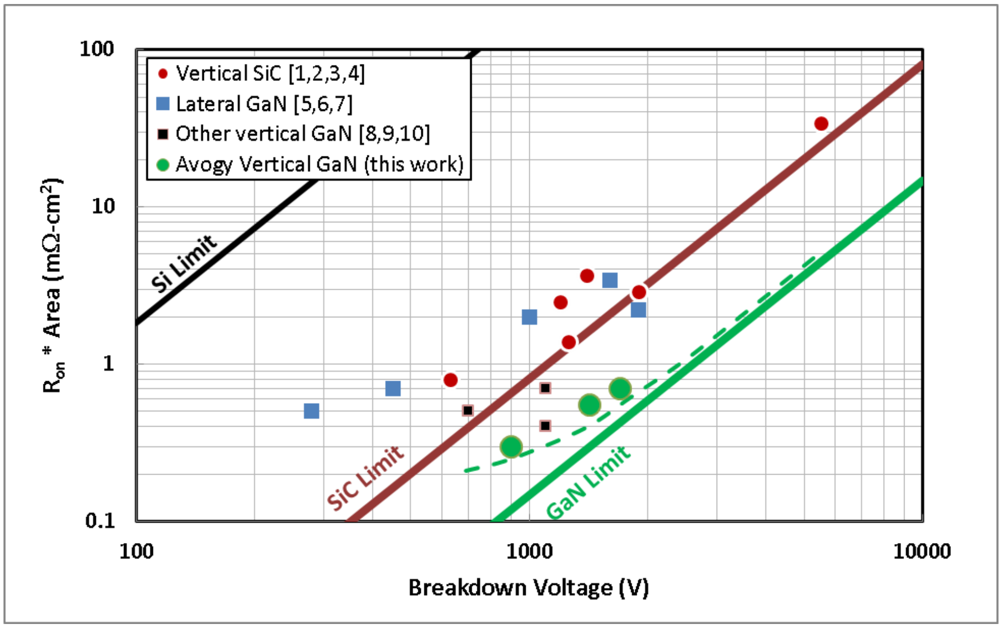

Fig. 3. Theoretical and reported specific on-resistance (R_{sp}) vs. breakdown voltage (BV).

The performance of these devices is far from the fundamental GaN limit. In fact, almost none of the reported lateral GaN devices have even surpassed the performance of SiC devices.[5,6,7] Clearly, to realize the full potential of the material properties of GaN, bulk GaN substrates should be used (also see previously published bulk GaN results[8,9,10] shown in black squares.)

The measured I-V-T (25°C to 175°C) reverse-bias characteristics of pn diodes indicate that the breakdown voltage has a positive temperature coefficient, i.e. the breakdown voltage is increasing with temperature, and hence the devices have avalanche capability. To explore further, pn diodes with breakdown voltages exceeding 1700 V were reverse biased and pulsed to 15 mA with 30-ms pulse width (Fig. 4.) It was found that the devices are robust to >30 W and 900 mJ of avalanche power. Contrary to common belief, we have proven that GaN devices do have avalanche capability.

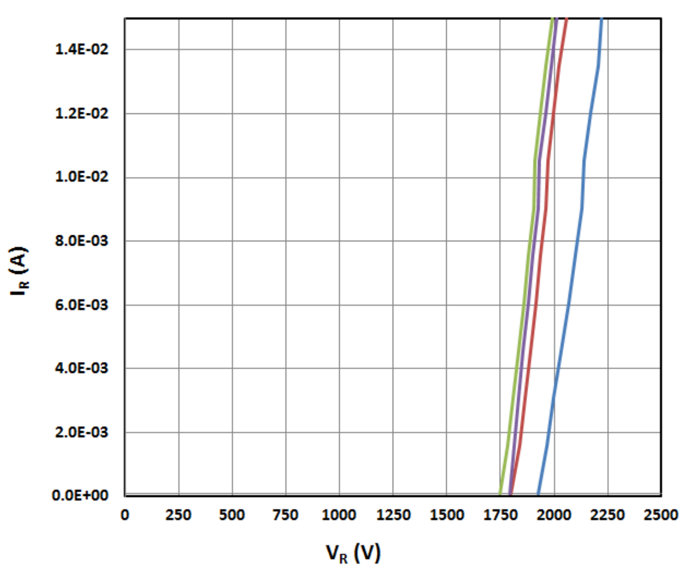

Fig. 4. GaN pn diodes with avalanche capability and >900 mJ of avalanche power.

Applications

The hard-switched boost circuit is one of the most commonly used topologies in power factor correction (PFC) for ac-dc power supply applications of >65-W power rating. Fig. 5 shows measured current and voltage waveforms across a pn diode in a typical boost circuit operating at 100 kHz. Avogy diodes were compared versus similarly rated (current and voltage) ultra-fast silicon rectifiers.

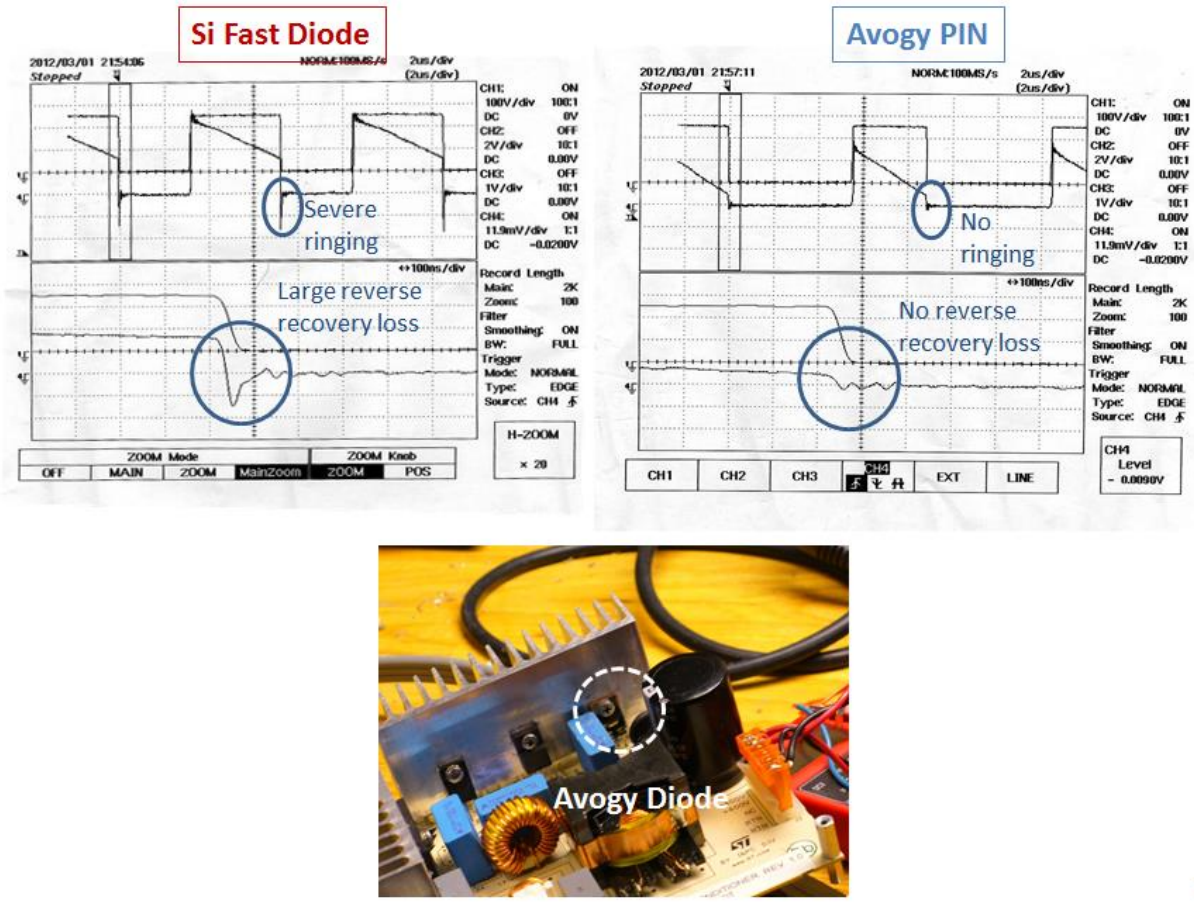

Fig. 5. Waveforms across diode element in a boost circuit topology.

In Fig. 5, the scope image on the left shows significant overshoot and ringing in the current waveform owing to the large reverse-recovery charge of the silicon rectifiers. The image on the right shows Avogy pn rectifiers in the same application. In this case, the reverse recovery is minimal and the low amount of ringing is mostly due to the inductance of the TO-220 package and the stray inductance present in the circuit.

The half-bridge configuration is the building block for many power topologies used in solar and wind applications. When a high-speed Si diode was replaced by the Avogy pn diode, a 4.6% efficiency improvement was measured at 100 kHz (Table 2.) The efficiency improvement delta between Si and GaN diodes will be much more pronounced at higher frequencies.

Table 2. Efficiency improvement in a 1000-V, 3-A half-bridge demonstration.

Material	Avogy GaN	Silicon
Efficiency at 100 kHz	96.7%	92.1%

These application examples demonstrate the effectiveness of GaN diodes in a simple drop-in experiment. However, efficiency improvements achieved by drop-in replacements are only one benefit of GaN. Advantages arising from system-level shrinkage as switching frequencies are increased is yet another. Applications such as motor drives, inverters for solar and wind, and inverters and battery chargers for hybrid/electric vehicles will all benefit from the size and efficiency improvements of power electronics based on bulk GaN.

Reliability

Ensuring long-term reliability is a key aspect of any new technology development and is especially critical for a new material system such as GaN. For high-voltage devices, high-temperature-reverse-bias (HTRB) testing is often the most important and challenging test. We have packaged our 1200-V pn diodes into industry-standard TO-220 packages and completed 1000 hours of HTRB stress at various voltages and temperatures. It has also been proven that GaN devices are avalanche capable (Fig. 4.)

Conclusion

In summary, vertical power Schottky and pn diodes have been demonstrated on low-defect-density bulk-GaN substrates with performance near the theoretical limits based on GaN material properties. Measured on-state and off-state dc characteristics for 600-V to 1700-V designs have been shown. Temperature characterization data, switching behavior in a boost circuit, and results from reliability testing have also been discussed.

Future work will include the productization of merged pn/Schottky diodes, vertical transistors for 600-V to 1700-V applications as well as the development of devices with breakdown voltages up to 5 kV. Avogy will be demonstrating its first products at APEC 2013.

References

1. D. Sheridan, A. Ritenour, V. Bondarenko, P. Burks, and J. Casady, "Record 2.8mΩ-cm^2 1.9kV Enhancement-Mode SiC VJFETs," Proc. of International Symposium on Power Semiconductors (ISPSD), pp. 335-338, 2009.

2. Furukawa, S. Kinouchi, H. Nakatake, Y. Ebiike, Y. Kagawa, N. Miura, Y. Nakao, M. Imaizumi, H. Sumitani and T. Oomori, "Low On-Resistance 1.2 kV 4H-SiC MOSFETs Integrated with Current Sensor," Proc. of International Symposium on Power Semiconductors (ISPSD), pp. 288-291, 2011.

3. T. Nakamura, Y. Nakano, M. Aketa, R. Nakamura, S. Mitani, H. Sakairi, Y.Yokotsuji, "High Performance SiC Trench Devices with Ultra-low Ron," IEDM Tech. Dig., pp. 26.5.1 – 26.5.3, 2011.

4. S. Balachandran, C. Li , P.A. Losee, I.B. Bhat, T.P. Chow, "6kV 4H-SiC BJTs with Specific On-resistance Below the Unipolar Limit using a Selectively Grown Base Contact Process," Proc. of International Symposium on Power Semiconductors (ISPSD), pp. 293-296, 2007.

5. N. Tipirneni, A. Koudymov, V. Adivarahan, J. Yang, G. Simin, M. Khan, "The 1.6-kV AlGaN/GaN HFETs," IEEE Electron Device Letters, vol. 27, no. 9, pp. 716-718, 2006.

6. Y. Uemoto, D. Shibata, M. Yanagihara, H. Isida, H. Matsuo, S. Nagai, N. Batta, M. Li, T. Ueda, T. Tanaka, D. Ueda, "8300V Blocking Voltage AlGaN/GaN Power HFET with Thick Poly-AlN Passivation," IEDM Tech. Dig., pp. 861-864, 2007.

7. Y. Dora, A. Chakraborty, L. McCarthy, S. Keller, S. DenBaars, U. Mishra, "High Breakdown Voltage Achieved on AlGaN/GaN HEMTs with Integrated Slant Field Plates," IEEE Electron Device Letters, vol. 27, no. 9, pp. 713-715, 2006.

8. K. Mochizuki, K. Nomoto, Y. Hatakeyama, H. Katayose, T. Mishima, N. Kaneda, T. Tsuchiya, A. Terano, T. Ishigaki, T. Tsuchiya, R. Tsuchiya, and T. Nakamura, "Photon-recycling GaN p-n Diodes Demonstrating Temperature-independent Extremely Low On-resistance," IEDM Tech. Dig., pp. 26.3.1 – 26.3.4, 2011.

9. Y. Hatakeyama, K. Nomoto, N. Kaneda, T. Kawano, T. Mishima, T. Nakamura, "Over 3.0 GW/cm^2 Figure-of-Merit GaN p-n Junction Diodes on Free-Standing GaN Substrates," IEEE Electron Device Letters, vol. 32, no. 12, pp. 1674-1676, 2011.

10. Y. Saitoh, K. Sumiyoshi, M. Okada, T. Horii, T. Miyazaki, H. Shiomi, M. Ueno, K. Katayama, M. Kiyama, T. Nakamura, "Extremely Low On-Resistance and High Breakdown Voltage Observed in Vertical GaN Schottky Barrier Diodes with High-Mobility Drift Layers on Low-Dislocation-Density GaN Substrates," Applied Physics Express, 081001, pp. 1 – 3, 2010.

About The Authors

Isik C. Kizilyalli is the CTO and founder of Avogy. Prior to founding Avogy, he held technical and management positions at Bell Laboratories (AT&T and Lucent Technologies), Agere Systems, Nitronex, and Alta Devices. His research, development, and commercialization experience covers a broad range of semiconductor materials (Si, GaAs, InP, and GaN), devices, and technologies (CMOS, BiCMOS, HFETs, detectors, HBT, photovoltaics). Kizilyalli is a fellow of the IEEE and was the recipient of the Distinguished Member of Technical Staff award by Bell Laboratories. He received a B.S. and Ph.D. degree in Electrical Engineering from the University of Illinois at Urbana. Kizilyalli has published 100 technical papers and has 45 U.S. patents.

Andrew Edwards is simulation and modeling manager at Avogy and has been involved with GaN since 1994. Prior to Avogy, Edwards was a device engineer at International Rectifier and before that, at Nitronex. Andrew has a bachelor's degree from Virginia Tech, and masters and Ph.D. from George Mason University. Edwards also served as a postdoctoral researcher at the Naval Research Laboratory in Washington D.C.

David Bour, chief scientist and head of MOCVD at Avogy has worked for nearly 30 years on semiconductor electronics and optoelectronics, and metal organic chemical vapor deposition, including UV-blue-green GaN-based LEDs and laser diodes, red AlGaInP lasers, telecommunication devices, strained quantum well lasers, mid-IR quantum cascade lasers, heterojunction bipolar transistors, and photovoltaic devices. Before Avogy, Bour was the chief technology officer of Applied Materials' Solid State Lighting Division and held positions at BridgeLux, Xerox Palo Alto Research Center's Electronic Materials Laboratory, Alta Devices, and Agilent Laboratories. Bour received a B.S. degree in Physics from MIT in 1983 and a Ph.D. degree in Electrical Engineering from Cornell University in 1987. His research is documented in more than 200 publications and 90 U.S. patents; and he is a fellow of the IEEE, for contributions to the growth and understanding of quantum well lasers.

Hemal Shah is the head of systems products at Avogy where Avogy's bulk GaN products are leveraged to make state-of-the-art power electronics systems. Prior to Avogy, Shah was the director, strategic marketing and applications at International Rectifier where he was responsible for new technology platform development, product strategy and tactical business development for a $400M product line. Shah has authored many IEEE publications and power electronics and technical magazine articles. He has an MSEE from RPI, Troy, NY and an MBA from IE business school, Madrid.

Hui Nie is the director of device technology at Avogy. He has spent nearly 20 years working on semiconductor electronic and optoelectronic devices; including GaAs, InP and InAlAs-based avalanche photodiodes (APD), PIN photodiodes, laser diodes and solar cells. Before Avogy, Nie was the lead solar cell designer at Alta Devices, and world recorder holder of the most efficient single-junction solar cell. He has held positions as director of product line management, director of advanced technology and senior engineer at Source Photonics, Finisar, Triquint and Lucent Technologies. Due to his contributions, InP-based APDs transitioned from R&D lab into mass production, and are now widely deployed around world in fiber-to-the-home (FTTx) applications. Nie received a B.S. degree in Physics from University of Sciences and Technology in China in 1993, and a Ph.D. in Electrical Engineering from the University of Texas at Austin in 1998. He is a senior member of IEEE for his contributions toward telecommunication APDs, receivers and transceivers.

Don Disney is the senior director of technology and product development at Avogy. He received his BSEE from Kettering University and PhD EE from Stanford University, and subsequently has held senior engineering and management positions at Delco Electronics, Power Integrations, Advanced Analogic Technologies, and Monolithic Power Systems. Disney's contributions to the field of power semiconductors span many technologies, including silicon-on-insulator power devices, IGBTs, high-voltage integrated circuits, Bipolar-CMOS-DMOS, and power MOSFETs. He has authored several IEEE papers and more than 100 U.S. patents.

For further reading on the GaN power devices, see the How2Power Design Guide, select the Advanced Search option, go to Search by Design Guide Category and select "Silicon Carbide and Gallium Nitride" in the Popular Topics category.