

Energy Efficient Wide Bandgap Devices

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Abstract. As wide bandgap devices begin to become commercially available, it is becoming clear that electrical efficiency improvement is one of the key drivers for their adoption. For RF applications, GaN HEMTs allow the use of highly efficient Class E circuit topologies demonstrating high powers of 63 Watts at 2 GHz with 75% power added efficiency. In broadband WiMax applications, GaN HEMTs offer very wide bandwidths while meeting the IEEE 802.16e standard with >25% drain efficiency. SiC Schottky diodes are allowing up to a 25% reduction in losses in power supplies for computers and servers when used in the power factor correction circuit. Even higher efficiencies can be obtained when the SiC Schottkys are combined with a SiC MOSFET as the switch, resulting in yet another 22% reduction in losses. For motor control, SiC Schottkys allow a >35% reduction in losses, as demonstrated for a 3 HP motor drive.

Introduction

After many years of intensive research on wide bandgap (WBG) semiconductor materials growth, processing techniques, and device design and fabrication, electronic devices made in SiC and GaN are finally starting to be commercialized and accepted by broad markets for their unique attributes. As the markets for these devices emerge, it is important to understand what drives the commercial market to use WBG devices versus other more established materials such as silicon or gallium arsenide. For RF amplifiers, obtaining good efficiency while meeting the required linearity specifications has always been a difficult challenge. GaN HEMT devices are now being used to demonstrate amplifier efficiencies far in excess of what can be shown in other technologies. This is achieved by either using their inherently good linearity, or by using Class E circuit topologies that were not possible at these high frequencies and power levels using Si or GaAs. In the broad area of power switching devices, there are a myriad of drivers and requirements, and there are many different attributes of SiC power devices that attract attention ranging from high temperature operation, high frequency operation, or extreme power levels that are not attainable any other way. However, the one underlying theme in virtually every application discussed is higher efficiency. The reason high temperature is attractive to many designers is that it allows them to dispense with cooling systems that are heavy and cause their own efficiency issues. These improvements in electrical efficiency can have a significant impact in reducing overall electricity consumption worldwide, impacting virtually every aspect of electrical usage, ranging from information technology to motor control, with potential savings in excess of \$30 billion/yr.

GaN HEMTs for Efficient Power Amplifiers

The drive for wide bandgap devices for RF applications is not only focused on high power, but also on improved efficiency. For RF devices, recent developments in the GaN HEMT have made it possible to realize highly efficient switch-mode amplifiers at microwave frequencies. GaN HEMT devices provide a very high ratio of peak current (I_{MAX}) to output capacitance, similar to GaAs PHEMTs. The major difference, however, is the significantly higher breakdown voltage associated with GaN HEMTs. Typical breakdown voltages are greater than 100 volts, enabling high power, high efficiency switch-mode operation at 2GHz and beyond.

Switch-mode power amplifiers based on GaN HEMTs have been designed and tested. At approximately 2GHz, amplifiers have been demonstrated to provide >60 watts of output power with an associated PAE of 75%, as shown in Fig. 1. Switch-mode amplifiers have previously shown high power and PAE at VHF, but this result is the first demonstration of class-E efficiency with high associated power at microwave frequencies. The unique combination of high current and high breakdown voltage afforded by wide-bandgap technology makes this result possible.

In addition to ultra-high efficiency compressed switch mode amplifiers, linear GaN transistors and amplifier reference designs have been developed to meet the IEEE 802.16(d) and (e) WiMAX specifications in the frequency bands of 2.3 to 2.9 GHz and 3.3 to 3.9 GHz for base-station and access point applications. These amplifiers exhibit average power levels of between 2 and 12 watts depending on the size of the transistors employed. The amplifiers produce gains of 12 to 16 dB depending on frequency range, have drain efficiencies at the required linear output power levels of >25%, consistent with EVMs of < 2.5%. The transistors are packaged in small ceramic flanged packages or surface-mount, leadless (QFN style) plastic packages. Unlike other transistor technologies such as GaAs MESFETs or Si LDMOS, the amplifiers have very wide instantaneous bandwidths enabling one amplifier design to cover many different frequency applications. Examples of these GaN HEMT amplifiers are shown in Figures 2 and 3, including operation at both 28 and 50 volts.

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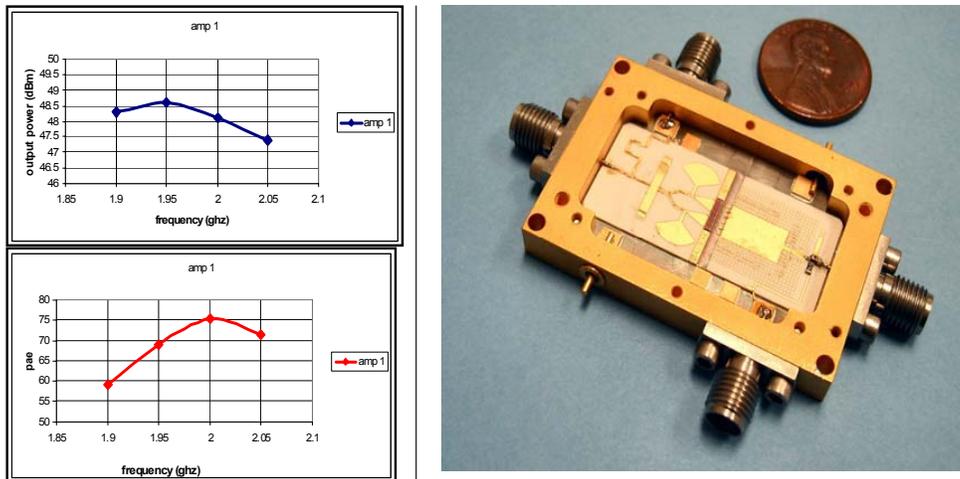


Fig. 1. GaN Switch-mode hybrid amplifier demonstrating an extremely high combination of power and efficiency: $V_{DS} = 30$ volts, 50 W input/output, 63 W P_{OUT} , 75% PAE, 2.0 GHz

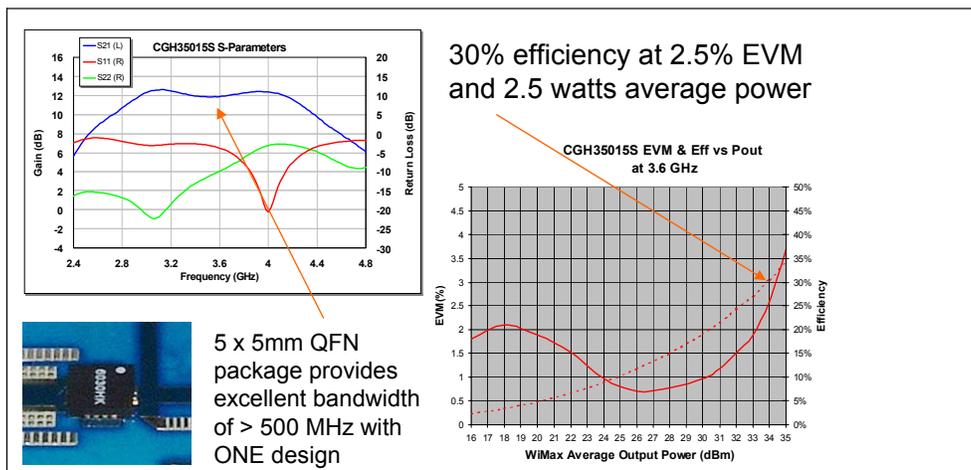


Figure 2. Performance of Cree 15 W GaN HEMT from 3-4 GHz with V_{dd} of 28 volts

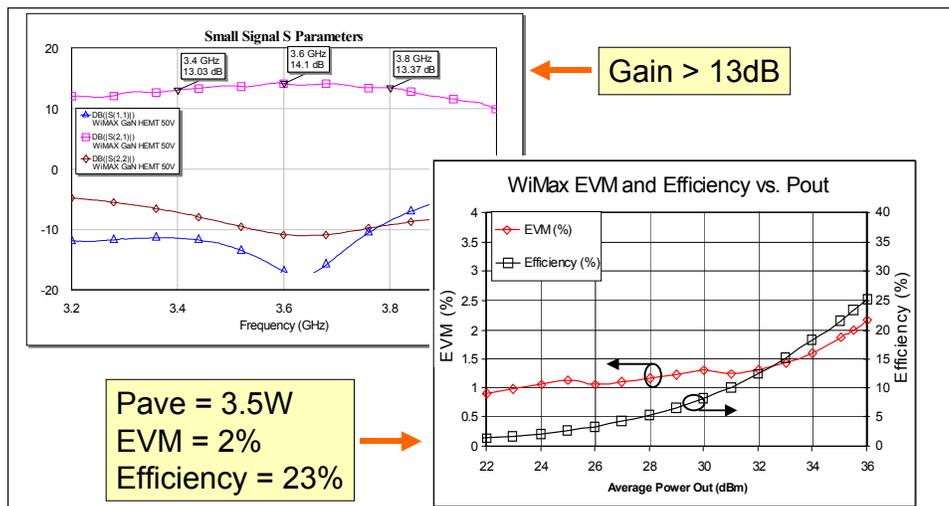


Figure 3. Performance of Cree GaN HEMT with higher V_{dd} of 50 volts from 3.2-4.0 GHz

SiC Power Devices

SiC Schottky diodes are now being accepted in the commercial market, predominantly in the area of power factor correction for switch mode power supplies (SMPS) for computer servers. The primary driver for this is to increase the efficiency of the SMPS, or increase its power density, or a combination of the two. This is enabled by the fact that there is no reverse recovery current during switching of the Schottky diode, versus the minority carrier recombination current of the silicon PiN diode that is being replaced. The typical efficiency improvement that can be obtained for a PFC circuit in a SMPS has been proven to be in the range of 2-5%, depending on the load and input voltage used [1]. This equates to a decrease in losses of up to 25%, since the average efficiency of the PFC circuit is currently in the range of 88-93%.

Another 22% reduction in losses can be obtained by pairing the SiC Schottky diode with a SiC MOSFET. The typical switch currently in use is a low on-resistance silicon MOSFET, such as Infineon's CoolMOS device. However, due to the high breakdown electric field of SiC, even higher doping levels can be used for the same blocking voltage, so lower on-resistances can be achieved. A comparison between a SiC MOSFET and an Infineon CoolMOS is shown in Fig. 4, where each of them has been paired with a SiC Schottky diode. One can see that at high output power levels, the SiC MOSFET offers a 1.6% improvement in efficiency, which equates to another 22% reduction in losses. This means that the total reduction in losses for an all-SiC PFC solution versus an all-Si solution would be in the range of 47%.

The other major application for SiC Schottky diodes is in motor control. Again, the lack of reverse recovery current allows a very significant improvement in motor drive

efficiency. The switching losses caused by the diodes in an inverter can account for 50% of the losses in the circuit. The reverse recovery not only leads to switching losses in the diodes, but this current is also dumped into the switch, affecting the switch turn-on and turn-off losses in the circuit as well. By switching to a SiC Schottky diode, one can not only eliminate the switching losses of the anti-parallel diode entirely, but the turn-on and turn-off losses in the standard Si IGBT can also be significantly reduced. To demonstrate this point, a standard motor drive for a 3 horsepower motor was measured with 600 V, 10 A silicon PiN diodes paired with Si IGBTs, and then comparative measurements were made with a 600 V, 10 A Schottky diode paired with the same IGBT. The circuit used is shown in Fig. 5. The resulting improvements in power loss are shown in Fig. 6. As expected the diode switching losses were eliminated entirely by using the SiC Schottky. The turn-on and turn-off losses in the Si IGBT were both reduced, resulting in a 56% reduction in total IGBT switching losses. The IGBT conduction losses of course stayed constant because the same part was used. Overall, a 35.4% reduction in losses was observed for this 3 horsepower inverter stage by simply exchanging the anti-parallel diode with SiC.

Global Impact of SiC and GaN Energy Efficiency

It is obvious from the examples above that SiC and GaN devices can offer significant improvements in efficiency for the applications discussed. The next question is what the impact of these improvements will be on total electrical usage. The breakdown of worldwide electricity usage is shown in Fig. 7 [2]. As one can see, motion control accounts for more than half of the electrical energy consumed. This includes motors for appliances such as washing machines, pumps and motors for industrial applications, and robotics. Additionally, another 16% of electrical energy goes to heating and cooling. Again, this

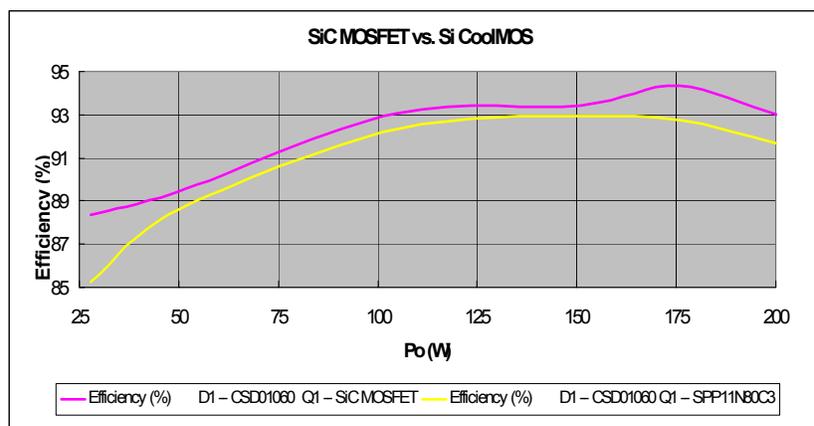


Figure 4. Efficiency versus output power for a PFC circuit using either a SiC MOSFET or an Infineon CoolMOS switch. Both are paired with a SiC Schottky diode.

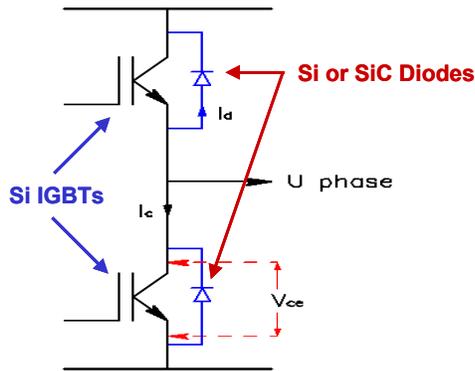


Fig. 5. Circuit diagram for a half bridge circuit of a 3-phase inverter for a 3 horsepower motor drive, using silicon IGBTs, and either Si PiN diodes or SiC Schottkys for the free wheeling diodes (FWD).

is largely powering motors for compressors and fans. As shown previously, SiC could offer very significant efficiency improvements across all of these applications when used with variable speed drives. The SMPS applications for SiC fall into the 14% of electricity used for information technology. This includes all of the power supplies for computers, servers, and telecom equipment. Additionally, the energy consumed for wireless broadcast falls into this category, thus the efficiency savings of the GaN HEMTs would also impact this category. Finally, lighting consumes the final 19% of electrical usage. While

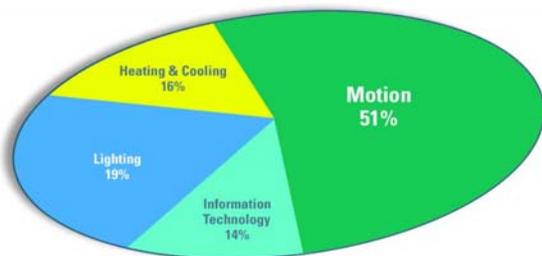


Fig. 7. Breakdown of worldwide electricity usage by application area [2]. SiC and GaN can impact all of these areas.

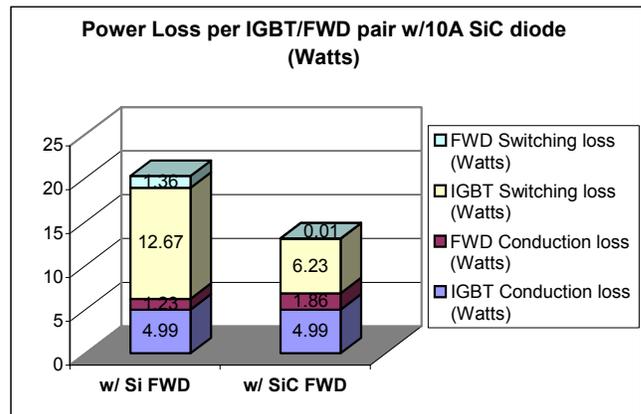


Fig. 6. Power losses for the half bridge circuit in Fig. 5 with a silicon PiN FWD and with a SiC Schottky FWD. A 35.4% reduction in power loss can be observed for the SiC FWD circuit for this 3 HP drive.

not discussed in this paper, SiC power devices can offer efficiency improvements in the solid-state ballasts for fluorescent lighting, in addition to the potential for GaN emitters for solid-state lighting. Therefore, SiC and GaN offer efficiency improvements across virtually every aspect of electrical usage! If variable speed drives were widely adopted across all motor control applications, the potential savings by using SiC versus Si in these drives, combined with the widespread use of SiC in SMPS and in GaN in RF applications, are estimated to be in excess of \$30 billion/yr!

Acknowledgements

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