ALGAN/GAN MOSHFET INTEGRATED CIRCUIT POWER CONVERTER

Department of Electrical Engineering
University of South Carolina
301 South Main Street
Columbia, South Carolina 29208
Pyteljr@engr.sc.edu

Abstract:
This work introduces the first step in a version of a wide-bandwidth, frequency-agile power interface that can sit between a simulation environment and real electrical hardware. Silicon (Si) technology is incapable of meeting the extreme switching demands of such a power interface, while gallium-nitride (GaN) technology is best suited for this application. A GaN power cell, in the form of an integrated H-bridge power block, is used as the core element in this new interface to take advantage of the III-V semiconductor material properties, resulting in enhanced operating characteristics. The GaN integrated H-bridge transistors are constructed out of AlGaN/GaN, MOS-Hetero-junction FETs (MOSHFETs). The H-bridge is mounted to an aluminum-nitride (AlN) substrate for heat removal via a thermally conducting, electrically insulating, epoxy. This wide bandgap power converter utilizes a high- and low-side driver to modulate the gate-source voltage of each device between +5 V and -12 V. Control for the power converter is provided via a dual output pulse generator. The pulse generator operates open-loop with two outputs to experimentally test the H-bridge in a half-bridge converter topology under different loading conditions.

I. INTRODUCTION

A. Material
The potential advantages of wide bandgap materials for power devices have been extensively discussed in [1-6]. It has been recently shown by the authors that the breakdown voltage, \( V_B \), of a planar junction device at low impurity doping concentrations is proportional to the bandgap energy, \( E_G \), in direct gap material as given in (1) [6].

\[
V_B \propto E_G^5 \quad (1)
\]

This physical relationship leads to a considerable advantage in wide bandgap materials, such as GaN, when considering the minimum on-resistance of a power electronic device (2).

\[
R_{\text{onsp}} = \frac{8.725 \times 10^{-7} V_B^2 E_G^{-0.75}}{\mu_e} \quad (2)
\]

The specific on-resistance value, \( R_{\text{onsp}} \), refers to a majority carrier device, specifically electrons because of the larger value of mobility, \( \mu_e \). \( R_{\text{onsp}} \) only accounts for the drift-region drop (e.g. ignoring other contributions to the device forward voltage drop during conduction), and \( R_{\text{onsp}} \) is normalized with respect to the cross-sectional area. Figure 1 shows the advantage of GaN, as compared to Si and 4H-SiC.

![Figure 1: Specific on-resistance as a function of breakdown voltage comparing unipolar devices made from Si, 4H-SiC, and GaN.](image)

B. Devices
It is known that AlGaN/GaN devices have high electron mobility, high saturation velocity, high sheet carrier-concentrations at heterojunction interfaces, high breakdown fields, low thermal impedances (when grown over SiC or bulk AlN substrates), and low on-state resistances [6-8]. AlGaN/GaN MOSHFETs were chosen over AlGaN/GaN HFETs for the H–bridge integrated circuit due to superior gate leakage current values [9]. These features make AlGaN/GaN MOSHFETs the most promising devices for high-speed and high-power converters. A typical
MOSHFTET structure is shown in Figure 2. The SiC layer provides the substrate material for device growth and acts as a heat sink and electrical insulator, while the AlN acts as a buffer to compensate the lattice mismatch between the GaN and SiC. Typical current-voltage characteristics of a 1 µm x 1 mm gate MOSHFTET are shown in Figure 3.

![Figure 3: Typical Current-Voltage Characteristics of a 1 µm x 1 mm gate single AlGaN/GaN MOSHFTET.](image)

Section II details several commercial applications for this emerging technology followed by an overview of the H-bridge circuit and driver in section III. Preliminary test results of the devices are shown in section IV and the conclusion is presented in section V.

II. APPLICATIONS FOR ULTRA-HIGH FREQUENCY CONVERTERS

This type of converter has several useful applications. At low to medium power levels, this ultra-high frequency (UHF) converter can be used as an audio amplifier. This type of system has the ability to greatly reduce the THD in modern audio amplifiers and simplify the control topologies required because AlGaN/GaN MOSHFTETs inherently have I-V curves that are fairly symmetric about the origin. Moreover, AlGaN/GaN MOSHFTETs can operate at much higher switching frequencies compared to Si, opening the possibility to realize an ultra high bandwidth switching power amplifier. An interesting application for such an amplifier is hardware-in-the-loop (HIL) processes. It could be used as a high-bandwidth power interface between software and hardware, giving more flexibility in the choice of the software-hardware interface point: in particular interface points with significant power flow could be chosen. Finally, since these switches are suitable for high temperature environments, due to their ability to function at higher junction temperatures, they are ideal for operation in extreme environments completely unsuitable for Si-based converters.

III. H-BRIDGE INTEGRATED CIRCUIT FOR CONVERTER

A. H-bridge

An integrated H-bridge converter consisting of four large-periphery AlGaN/GaN MOSHFTETs was fabricated on a SiC substrate and arranged as shown in the schematic of Figure 4. The overall size of the H-bridge device is 1.90 mm x 1.25 mm. Each of the four devices comprises of six 200µm gate fingers in parallel and therefore has a total width of 1.2mm. The IC was mounted on a 0.025 inch thick AlN substrate using a non-conductive thermal epoxy. Gold wire bonds make the electrical connections between the device and the gold traces on the AlN substrate. Photographs of the H-bridge IC and AlN substrate are shown in Figures 5 and 6 respectively. All signals enter and leave the gold substrate conductors via SMA connectors.

![Figure 4: Schematic of integrated AlGaN/GaN H-bridge](image)

![Figure 5: AlGaN/GaN H-bridge Converter](image)

![Figure 6: Photograph of AlGaN/GaN H-bridge IC and AlN substrate](image)
IV. EXPERIMENTAL CIRCUITS AND RESULTS

A. Overview of the Testing Scheme

The experimental results are preliminary and greatly limited by the switching speed of the driver. Future tests will better explore the advantages of AlGaN/GaN MOSFETs.

The H-bridge testing was performed in three stages. First static tests were performed using a probing station, prior to dicing of the GaN wafer; this determined the maximum operating current and gate leakage of the devices. The second stage consisted of individual switching tests, while the final stage consisted of performing half-bridge converter topology experiments.

B. Static Tests

All static tests shown in Fig. 8-10 were performed on neighboring single devices fabricated on the same GaN wafer where the H-bridge was fabricated. Typical forward I-V characteristics of a 100-µm device are shown in Figure 8. The current of a smaller device is measured due to self heating in larger periphery AlGaN/GaN devices. The value of the current in the larger device is then obtained by multiplying the current by the size of the larger device. The maximum current of these 1.2 mm devices at +3 V\text{GS} may be obtained by:

\[ I_D = \frac{0.13 A}{100 \mu m} \times 1.2 mm = 1.56 A \quad \text{for } V_{GS} = +3 V \]

Additionally, gate leakage tests were performed and the results are shown in Figure 9. The gate leakage current of the device is approximately 70 nA for \( V_{GS} = 15 \) V.
Figure 9: Gate leakage current of a similar device with $V_{DS} = 0$.

The unity gain frequency, $F_T$, has been measured. The $F_T$ of a similar device having a two-fingered gate (compared to a six finger gate) is shown in Figure 10. It has previously been shown that $F_T$ is basically independent on the number of gate fingers [11-12]. Therefore, we can estimate $F_T$ for our device to be approximately 12 GHz. This is consistent with results reported in [11] for similar AlGaN/GaN MOSHFETs showing a unity gain frequency $F_T$ of 9.5 GHz.

Figure 10: A similar two-fingered AlGaN/GaN MOSHFET gate device showing a current gain $F_T$ of about 13 GHz and a maximum oscillating frequency of 42 GHz.

C. Device Switching Tests

The second testing stage consisted of performing individual switching tests to characterize the rise and fall time of the devices while conducting current. It is our belief the results of these tests are severely limited by the switching speed of the gate drive circuit. A LeCroy scope with a bandwidth of 500 MHz was used to perform the measurements along with a LeCroy differential voltage probe having a bandwidth of 200 MHz. The LeCroy current probe used has a bandwidth from DC to 50 MHz. Figure 11 confirms our opinion that the driver severely limits the device’s switching speed by showing the slow rise and fall times of the gate driver waveforms. The rise time of the gate driver circuit is 211 ns and the fall time is 157 ns. The 50-$\Omega$ load resistor used in the circuit has a fairly large parasitic inductance associated with it ($L_{\text{load}} = 9.3 \mu\text{H}$). For this reason the load current lags the load voltage.

Figure 11: These waveforms show the output of the gate driver circuitry used to drive device #2 and device #4. The switching frequency is 200 KHz with approximately 200 ns of dead time.

The experimental circuit used to test device 2 may be seen in Figure 12 and the experimental results are shown in Figure 13. A rise time of 100 ns and fall time of 101 ns was obtained for device #2 for an operating current of 530 mA. In Fig. 13 it can be noticed that the voltage drop during conduction is larger than 10 V, therefore larger than what one would expect from the static curve of Fig. 8 (after proper scaling). This can be attributed to the so-called current collapse effect [13], which causes these devices to have a larger voltage drop when operated in a pulsed fashion.

Figure 12: Experimental set up used to test switching time of device #2.

Figure 13: These waveforms show the output of the gate driver circuitry used to drive device #2 and device #4. The switching frequency is 200 KHz with approximately 200 ns of dead time.

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Figure 13: This shows the rise and fall time of device 2 for the schematic shown in Figure 12. The forward voltage drop of device 2 is shown for a current of 530 mA.

Figure 14 shows the schematic for the testing of device #4. This testing was performed under the same conditions as device #2. The switching test results for device #4 are illustrated in Figure 15. A rise time of 95 ns and fall time of 88 ns was obtained with a switching current of 598 mA.

D. Half-bridge Converter Testing

The final phase of testing consisted of operating the H-bridge as a half-bridge converter at 200 KHz. Devices 2 and 4 were used for the testing. The converter control was supplied by a dual channel pulse generator. These signals were fed to the driver and the driver output results have been previously shown in Figure 11. Approximately 200 ns of dead-time were introduced to prevent cross conduction. This dead-time was predicated by the switching speed of the drivers. The schematic for the half-bridge converter is shown in Figure 16. The input voltage was 40 V and was split to allow for positive and negative operation of the half-bridge converter. Resistors R1 and R2 are used to bias the common point to VDD / 2, and the capacitors are used to filter out any high frequency noise. The 50-Ω load resistor used in the circuit resistor has a fairly large parasitic inductance associated with it (LRLoad = 9.3 µH). This results in a smoother current transition during the dead time.

Figure 16: Experimental setup used to test the AlGaN/GaN MOSHFET half-bridge converter.

Figure 17 details the half-bridge converter results from the schematic shown in Figure 16. The load current is slightly filtered due to the parasitic inductance of the load. The load voltage was taken using a LeCroy differential voltage probe with a bandwidth of 200 MHz, while the current was obtained by a LeCroy current probe that had a
bandwidth from DC to 50 MHz. Figure 18 depicts the same information as Figure 17 but at .2 µs/div versus 1 µs/div.

![Graph showing VGS2 (5 V/div), VGS4 (5 V/div), VLoad (20 V/div), ILoad (200 mA/div), and 1 µs/div.](image)

**Figure 18:** Half-bridge converter testing at 200 KHz. The input voltage was 40 V and the time scale is .2 µs/div.

### IV. CONCLUSION

Experimental results from a half-bridge AlGaN/GaN MOSFET converter have been shown. Along with the converter operation, switching tests have been shown for two of the four devices on the H-bridge. The rise and fall time of the devices has been shown to be approximately 90 ns. The rise and fall time of the device is limited based on the current driver design and future work will bring improved results as the driver design becomes faster. The results are preliminary, but have potential. Some static tests have been performed on similar devices that neighbored our H-bridge on the GaN wafer prior to dicing. These show a maximum current of approximately 1.56 A, and an F<sub>T</sub> of approximately 12 GHz has been obtained for similar devices. These results provide great promise for the future in high power applications where high speed is required and high temperatures are present.

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### REFERENCES


