The Development of SiC MOSFET-based Switching Power Amplifiers for Fusion Science

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EAGLE HARBOR TECHNOLOGIES

Introduction:

During the past decade, the state of the art in power semiconductors has advanced significantly. The introduction of silicon carbide (SiC) semiconductor devices provides advantages of fast, high-temperature and/or high-voltage devices. EHT has previously developed a proprietary gate drive system for IGBTs, which enables extremely precise, fast, and efficient switching. The goals of this program were as follows:

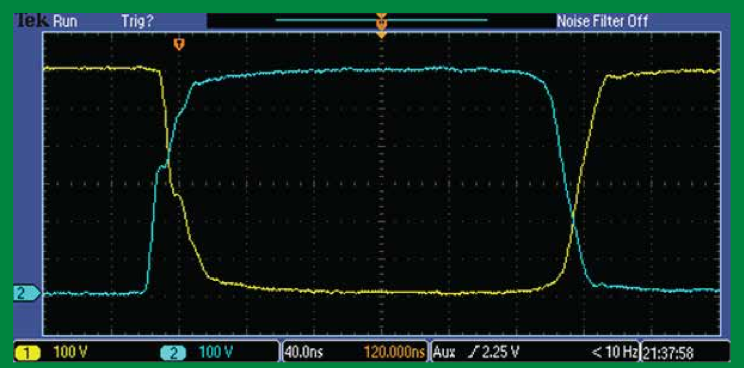
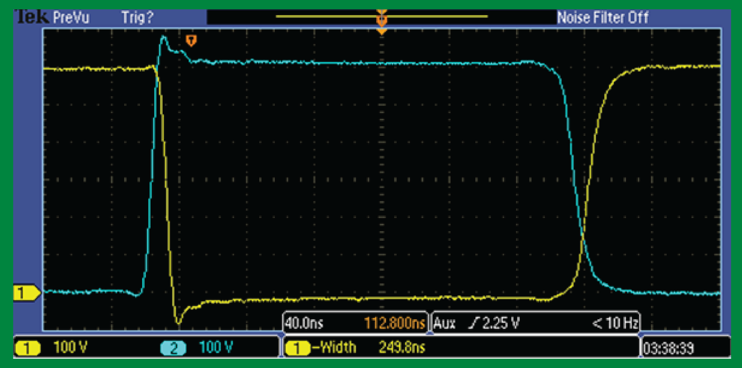
- Investigate the efficacy of the EHT gate drivers with SiC MOSFETs.
- Develop a full-bridge switching power amplifier capable of producing high current and voltage pulses at high pulse repetition frequency (PRF) with variable duty cycle.

This power system was initially designed for driving coils for fusion science and plasma physics experiments; however, it also has applications within the etch, ion implantation, and sputtering markets.

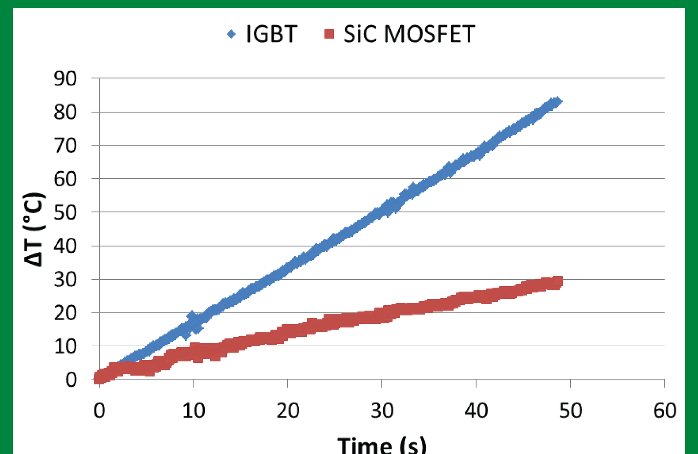
Motivation and HIT Experiment:

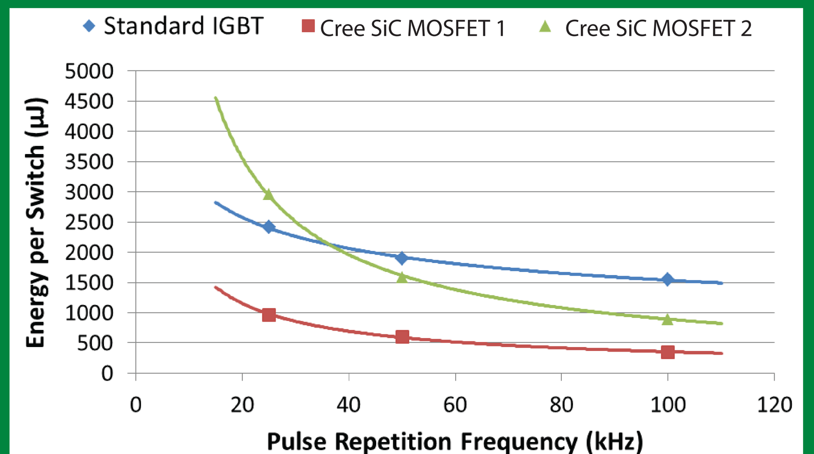
EHT surveyed commercially available SiC MOSFETs and IGBTs and selected devices for in house testing based on maximizing switching and conduction efficiency at the highest possible current per device. The goals of this testing were to investigate if the EHT gate drive technology would improve SiC MOSFET switching, measure the overall switch efficiency, and determine the maximum current per device.

Manufacturer	Switch Description	Rated DC Current (A)	Rated Pulsed Current (A)	Current at which Rated Values are Specified (A)	Rated Rise Time	Measured Rise Time, 12 A (ns)	Measured Rise Time, 24 A (ns)	Rated Fall Time	Measured Fall Time, 12 A (ns)	Measured Fall Time, 24 A (ns)
IR	IGBT	40	120	20	20	12	26	24	31	21
Microsemi	IGBT	40	160	40	25	4	5	40	30	10
IR	IGBT	50	105	35	25	5	6	105	50	12
Microsemi	IGBT	75	100	25	10	4	5	20	29	7
IR	IGBT	80	160	40	46	6	9	28	50	29
ST Microelectronics	IGBT	80	160	40	15	5	5	135	281	201
IR	IGBT	90	90	30	36	6	9	74	20	10
ROHM	SiC M	14	35	4	19	12		29	17	
ROHM	SiC M	20	45	10	17	10		16	9	
Cree	SiC M	24	49	10	21	12	39	34	17	18
Cree	SiC M	36	80	20	20	5	9	19	15	5

(Left) Voltage waveforms for two full-bridge legs (Blue & Yellow) and oscillating voltage on the resonant network. (Right) Oscillating current in the resonant network.

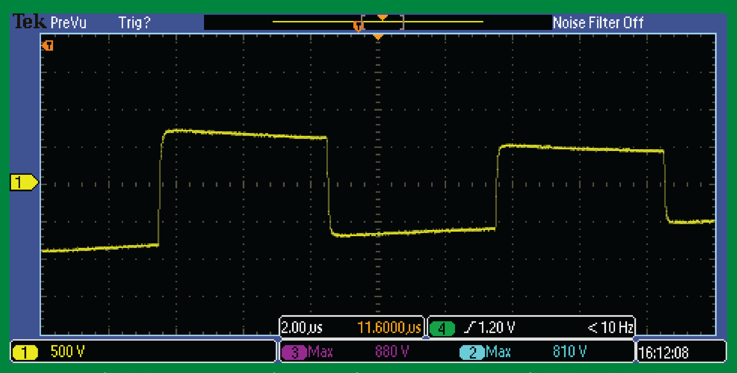




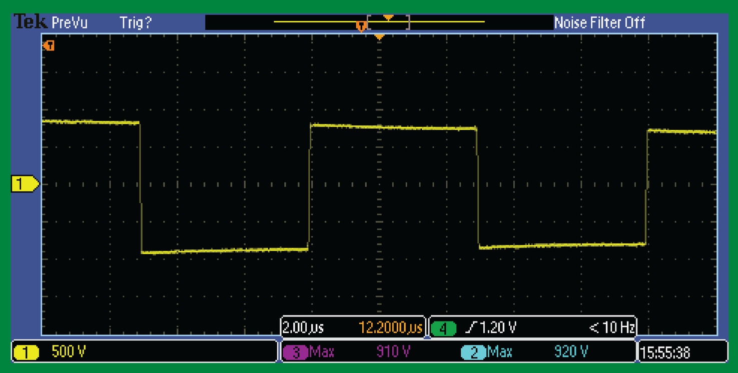
Thermal tests conducted at 600 V and 24 A/device. (Left) IGBT and SiC MOSFET temperature change showing lower total energy loss for the SiC MOSFET device. (Right) Energy dissipation per switching cycle at various pulse repetition frequencies.

Full-Bridge Testing with Resistive Load:

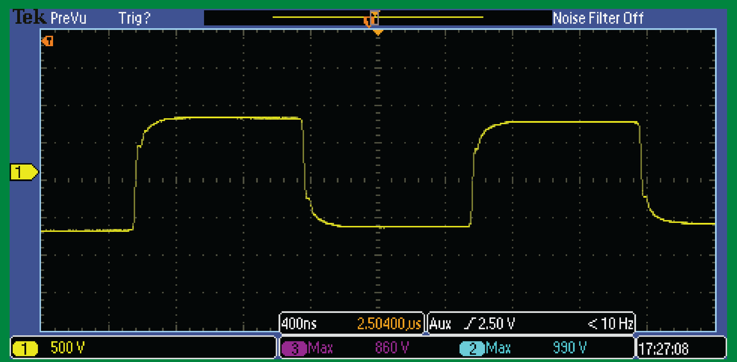
EHT has conducted full-bridge testing into a variety of low-inductance resistive loads to demonstrate high power switching and clean waveforms. Below are sample waveforms from this testing.



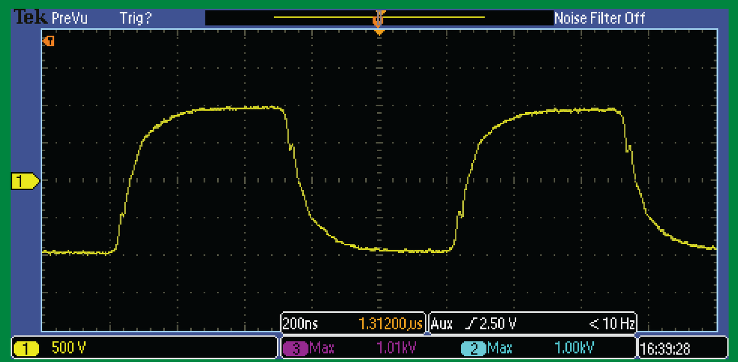
1.8 kV_{pk-pk} and 2.9 kA at 100 kHz PRF.



1.8 kV_{pk-pk} and 720 A at 100 kHz PRF.



1.5 kV_{pk-pk} and 8 kA at 500 kHz PRF.

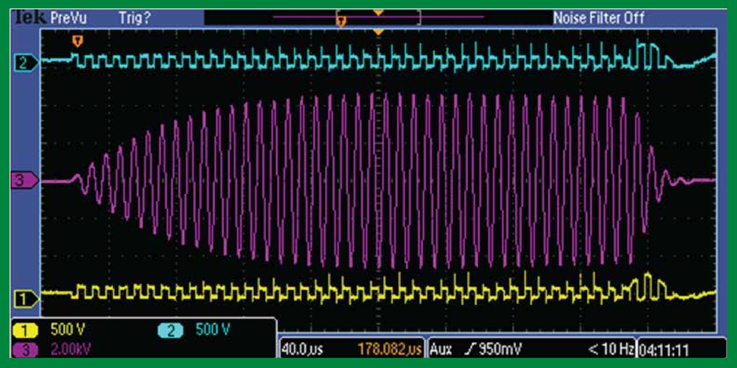
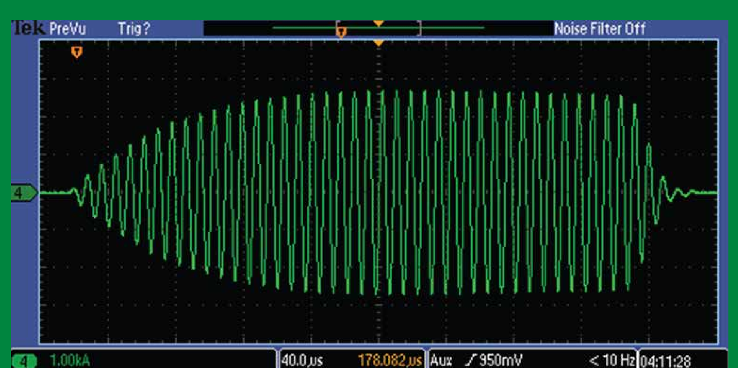


2.0 kV_{pk-pk} and 3.2 kA at 1 MHz PRF.

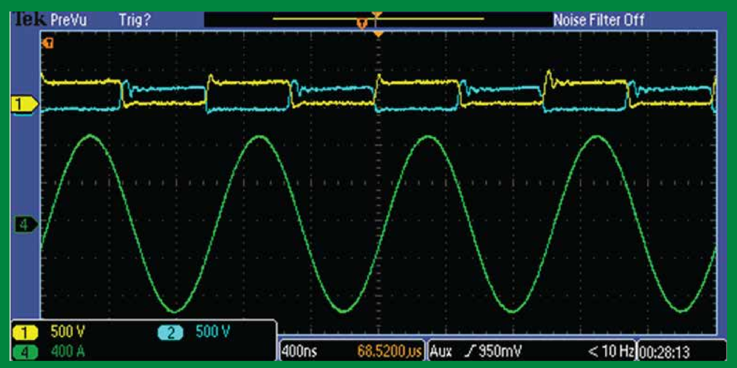
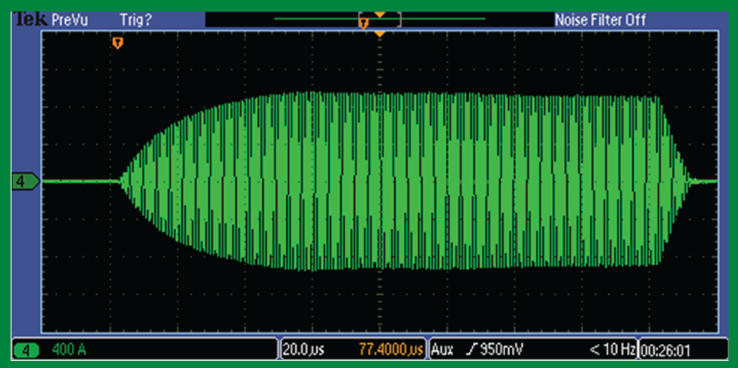
Full-Bridge Testing with Series Resonant Tank Circuit:

EHT tested the ability of the full-bridge to drive a series resonant tank circuit at two resonant frequencies. During the high frequency test, the full-bridge achieved a peak-to-peak current of 5.4 kA. The 1 MHz switching test achieved 1 kA through the resonant load. The limitation of both tests was the voltage rating of the series resonant capacitor. The both tests demonstrated capability for precision magnetic control with fast PWM.

	High Frequency	Very High Frequency
Resonant Frequency ($\omega_0/2\pi$)	120.9 kHz	1 MHz
Charge Voltage	150 V	300 V
Total Storage Capacitance	25 mF	128 μF
Resonant Inductance	1.7 μH	2.5 μH
Resonant Capacitance	1.0 μF	10 nF
Oscillating Current (pk-pk)	5.4 kA	2 kA

(Left) Voltage waveforms for two full-bridge legs (Blue & Yellow) and oscillating voltage on the resonant network. (Right) Oscillating current in the resonant network.

(Left) SPA switching waveforms (Blue & Yellow) and resonant network oscillating current. (Right) Resonant network oscillating current for a pulse length 100 μs.

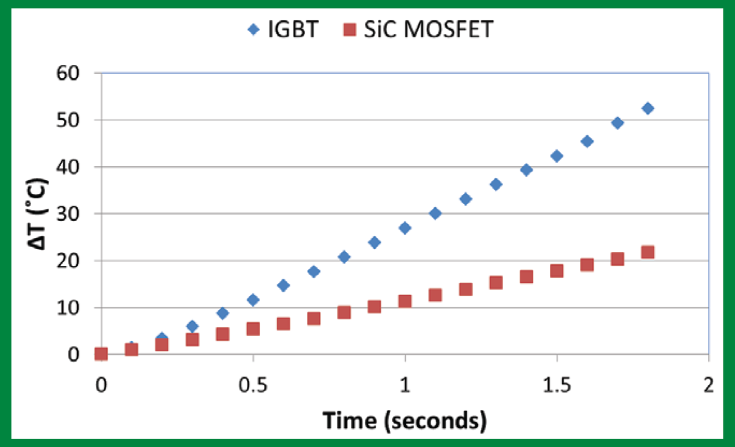
Acknowledgments:

This work was supported by the U.S. Department of Energy (DE-SC0011907).

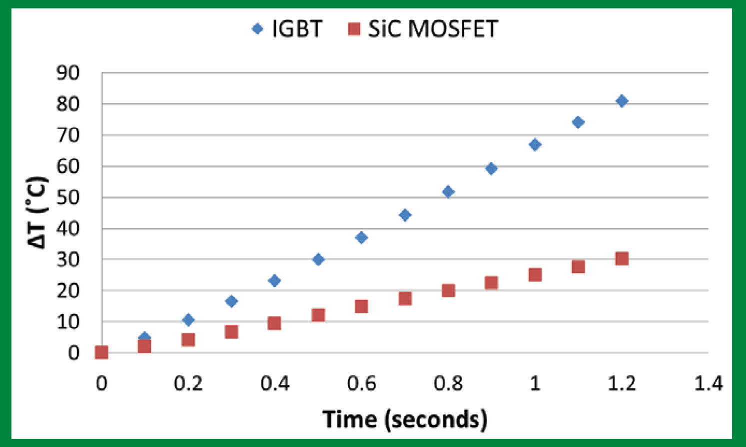
Thermal Management:

Using both the IGBTs and Cree SiC MOSFETs, the thermal response of the full-bridge was measured with a thermocouple on the solid-state switch:

- Resistive load testing used a pulse width of 250 ns at 100 kHz, 600 V and 24 A/device.
- Resonant load testing used a charge voltage of 600 V and was driven at the resonant frequency (115 kHz).
- In both cases, the temperature change of the IGBTs was 2-3 times greater than that of the SiC MOSFETs. This means the use of SiC MOSFETs can significantly reduce the thermal management requirements of the system.



Comparison of the IGBT vs SiC MOSFET heating into a resistive load.



Comparison of the IGBT vs SiC MOSFET heating into a resonant load.

Conclusions

EHT is developing a full-bridge pulser capable of driving resistive, inductive, and tank circuit loads with the following characteristics:

- Galvanic isolated output (can be biased with respect to other systems)
- Pulse width can be varied in real-time with duty cycle from 0-100%
- High PRF (> 1 MHz), adjusted in real-time
- Output voltage: 2.0 kV_{pk-pk} (or 10s kV with built in step-up transformer)
- Output current (1 ms): 10 kA_{pk-pk}
- Output current (10 ms): 6 kA_{pk-pk}
- Compact form factor
- Efficient

First generation EHT full-bridge pulser.

These pulsers have applications within the fusion community for driving antennas and tank circuits. Similar devices are used in other research areas including linear particle accelerator supplies, high voltage ion implantation supplies, RF cyclotron power supplies, high power pulse width modulation (PWM) amplifiers, and high power trigger systems. This system will allow for new capabilities for etch, ion implantation, and sputtering applications within the materials science and semiconductor processing communities.

Further Information:

For more information on the SiC full-bridge or other switching power supplies please visit our website (http://www.eagleharbortech.com) or email.