PowerBox: A Modern Power Electronics Education Toolbox Using Si and SiC Devices

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***Abstract*—This paper discusses the need and design for a new power electronics educational board. This teaching board features the ability to be used in DC-DC, DC-AC, and AC-DC instructional labs. The board utilizes silicon (Si) and silicon carbide (SiC) technologies, the latter of which being under minimum examination in existing educational labs. This board is intended to be an open-source product that is available for external ordering at production costs. This paper details the design of the board, including schematics, layouts, and bill of materials. An example lab with the board implemented into a buck converter is also demonstrated.**

***Index Terms*—Power electronics education, silicon carbide SiC, instructional laboratories, laboratory equipment, DC and AC converters, teaching demonstration**

I. Introduction

Power electronics education, at its core, requires a hands-on learning experience to introduce students to its many facets at circuit level [1]. Through labs, students gain a deeper understanding of the course topics and the circuit topologies. Existing teaching tools such as the University of Minnesota/Vishay Dale Power Pole board [2][3], or the University of Illinois Blue Box project [4], are useful for teaching the origins of power electronics but are archaic, being more than 15 years old. The Power Pole board [2], for example, contains a modular system that offers simple procedures to teach students about DC-DC converters but does not feature support for AC labs [3]. On top of this, designed in the early 2000s, The Power Pole Board does not include recently developed technologies. The Blue Box project, created at the University of Illinois, is capable of teaching AC labs but is based around 20-year-old technology [4], which means that the Blue Box also falls short when it comes to teaching emerging topics. An updated teaching board desires recent technology such as wide band-gap semiconductor devices, integrated chips, etc., which are unaddressed in most university introductory instructional labs. It is imperative that a new teaching module is designed to facilitate the teaching of the legacy course material alongside modern technologies, implemented in a single modularized product.

We propose a state-of-the-art power electronics teaching board, namely the PowerBox. This equipment supports AC-DC, DC-AC, and DC-DC labs. The toolbox features both Si and SiC devices, allowing for a hands-on opportunity for students to learn about the advantages and disadvantages of emerging power semiconductors. This new instructional board also features new integrated chips that decrease equipment sizing while maintaining functionality. Finally, this board must be modular to create customized circuits and to engage students to learn about the effects of gate resistance on switching behavior. The PowerBox utilizes a user-friendly design to switch between either semiconductor devices or circuit topologies efficiently.

This paper will discuss how we design the PowerBox and how it meets the requirements. Then we will move onto an overview of the features of the proposed board before continuing to some of the issues we encountered during the design process. A hardware prototype and the results of a sample student-oriented experiment will demonstrate the design efficacy.

II. Technical Background

The proposed PowerBox is based around the Illinois Blue Box approach, as laid out in [5]. Other standard power electronics instructional laboratories use a “black-box” method, which provides a function or output that students are expected to build their circuits around [5]. The Blue Box approach instead offers students the circuitry inside the power converter of construction, promoting a deeper understanding of the converter circuits [5][6]. Balog, Krein, et al. [7][8] build upon this, mentioning the system-level design out of the Blue Box method that results in increased student involvement, which stems from an understanding of the systems within the Blue Box. In [9], a restructuring of a power electronics course is laid out with an emphasis on preparing students for careers in research or industry. This restructuring provides students with an elevated understanding of the devices and components operated within power electronics [9]. Other advantages of laboratories structured in this manner are laid out by Panaitescu, Mohan, et al. in [10].

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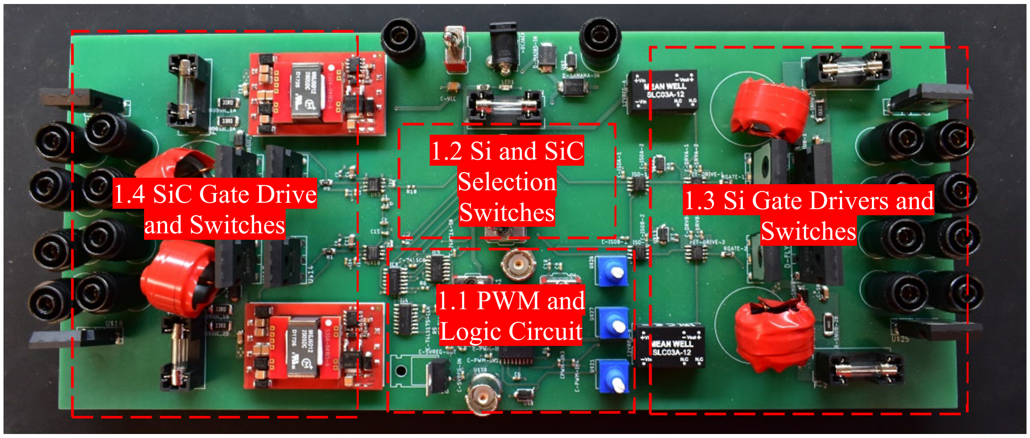

Figure 1: Picture of the in-house designed PowerBox board.

In current introductory labs (targeting undergraduate seniors), there is a minimal examination of SiC or wide-bandgap devices. This absence of student introduction to SiC technology leads to a lack of knowledge in the comparisons to standard Si devices. Some advantages are faster switching speeds, lower switching losses, and higher breakdown voltages [11][12]. The reduced switching losses are brought about by low capacitance between the terminals and lower on-voltage drops [13] when compared to Si devices. SiC can also operate at higher temperatures [12].

Along with these advantages, students can investigate the disadvantages of SiC technologies. One of the drawbacks is a complicated gate drive design [14]. Capacitances and transconductance are lower in SiC MOSFETs [14], meaning that gate voltages must be higher for turn on (approximately 20 V) and minimum negative $V_{GS,MIN}$ around -5 V [14]. These factors lead to differences in board design between Si and SiC devices.

III. PowerBox Design Details

PowerBox features the same modularity as the Illinois Blue Box and will be capable of using similar manuals and steps within instructional labs. The PowerBox differs in the fact that it utilizes new IC and semiconductor technologies. The design of the PowerBox board can be split up into four functional blocks described in the following paragraphs.

Figure 1 showcases the complete in-house designed PowerBox board. The board features four independent switching blocks. Two of the switching blocks use standard Si MOSFETs (Infineon CoolMOS™ CFD7, *1.3 in Figure 1*). The other two switching blocks use SiC MOSFETs (Rohm SCT2160KEC; *1.4 in Figure 1*). Along with the MOSFETs, each block includes a separate diode (IXYS DSEI30-06A), which can be used in conjuncture with the FETs when incorporated into a lab. Students can choose between Si and SiC by actuating two independent switches *(1.2 in Figure 1)* that allow for side by side analysis of the two device physics.

An onboard configurable PWM circuit controls the switching actions of the MOSFETs *(1.1 in Figure 1)*. A potentiometer and a toggle switch change the frequency of the PWM. Duty Ratio is modified using a separate potentiometer, which can be substituted by a higher quality adjustment knob. BNC connections are also present to allow for PWM control via an external analog signal from a signal generator or similar equipment. The PWM signal then goes into a digital logic circuit *(1.1 in Figure 1)*. This function acts to increase the frequency and change the duty ratio further. The digital logic breaks the single PWM into two separate signals.

The entire board is powered off a 12 V DC source, not including the power circuit to be constructed by the students. The power circuit of the board is designed to handle up to 600 V DC. However, due to safety, students only limit to voltages below 60 V DC. The expected current values peak around 1-2 A, although the parts can handle current up to 10 A. The switching frequency ranges from 750 Hz up to 250 kHz.

A. *PWM Circuitry*

The PowerBox includes an on-board PWM controller (TI UC 3526DW). Figure 2 provides the design schematics of this PWM controller. The duty ratio of the PWM signal generated by the controller is set by three separate 5 kΩ potentiometers (Bourns 3310Y-001-502L). A 50 kΩ potentiometer (Bourns 3310Y-001-503L), as well as a switch that changes the capacitance connected to the CT pin on the PWM controller, configures the frequency of the PWM. The PWM controller can also receive input from the BNC jack. This external connection can be used to provide a reference waveform and create a more complex PWM signal.

From the PWM controller, the signal travels to a series of logic ICs (*Figure 9 in the Appendix*). These act to do several things:

1. Split signal Q into two signals, Q1 and Q2.
2. Shift one signal, Q2, so that it is 180° out of phase with reference signal Q1.
3. Add deadtime split signals, Q1 and Q2.

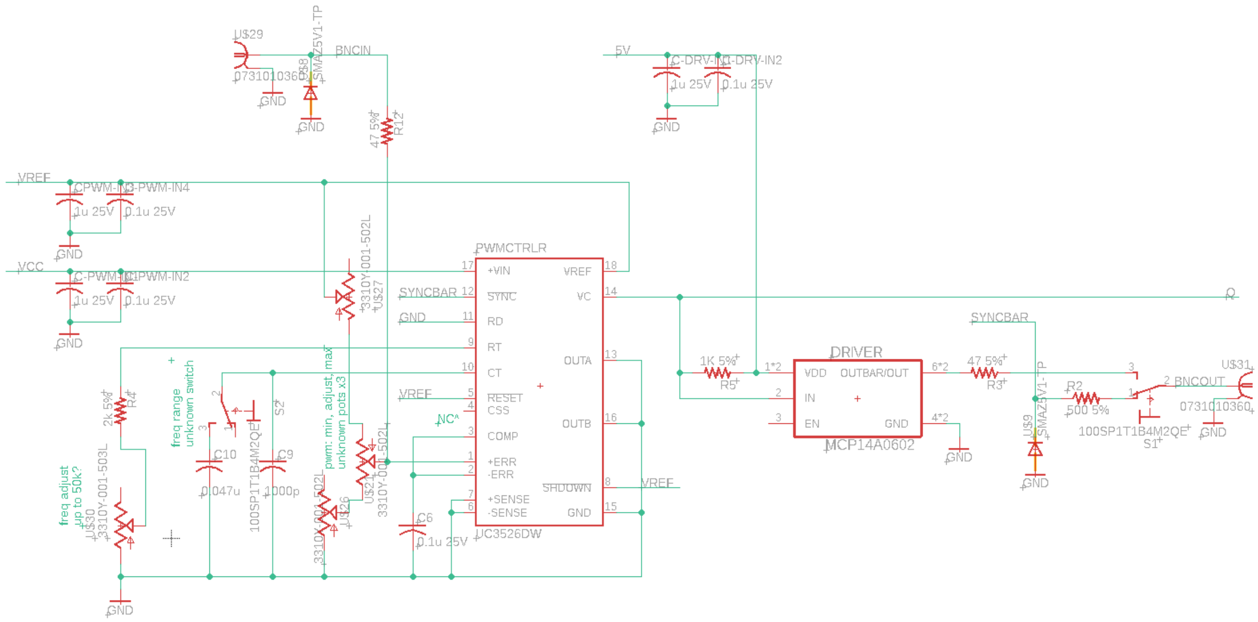

Figure 2: PWM controller schematics.

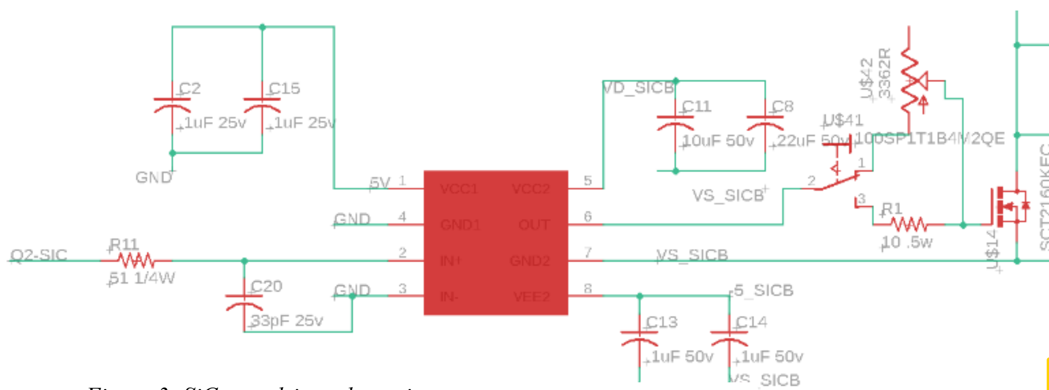

Figure 3: SiC gate drive schematics.

After the signal travels through the logic circuitry, it comes to a three-way switch. This switch enables three different settings for the output signal going to the gate driver circuitry:

1. Q1 and Q2 identical.
2. Q1 and Q2 separated with a 180° phase shift.
3. Q1 and Q2 180° out of phase from one another with deadtime.

B. SiC MOSFET Gate Drive Circuit Design

Figure 3 shows the design schematics of the SiC gate drive circuitry. The SiC MOSFET necessitates the use of a more complex gate drive circuit compared to that of a Si device. This complexity stems from the fact that SiC MOSFETs possess a lower transconductance, which results in higher turn-on voltages and lower minimum gate-source voltages for turn-off [14]. The SiC MOSFET chosen in the new teaching board is Rohm SCT2160KEC, which has a recommended $V_{GS,ON}$ of 20 V, and a $V_{GS,OFF}$ of -5 V. A new isolated power supply, Murata MGJ6, was chosen to supply the driver circuit with the higher $V_{GS,\ ON,}$ and the negative $V_{GS,\ OFF}$. Upon further inspection, the original gate driver IC for the Si devices was not able to handle the voltage difference introduced by the new supply. To mend this, a new driver IC was selected. TI UCC530E isolated gate driver offered a higher voltage difference and the ability to provide a negative gate drive required. The new gate drive IC called for the redesign of the gate drive resistor as well. Referring to Figure 3, note the addition of a switch (*U$41 in the*

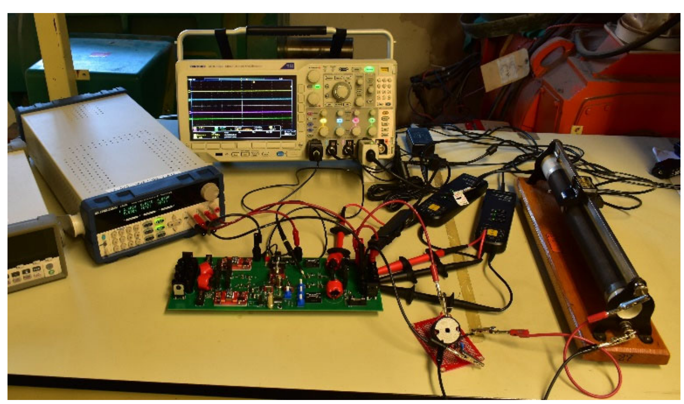

Figure 4: Buck converter setup. In the middle is the PowerBox board. The red board in the center right contains a 100 uH inductor and a 10 uF capacitor. The load is set to about 20 Ω. In the foreground is the Tektronix MDO3024 Oscilloscope and the BK Precision 9132B DC power supply that was used for testing.

figure). This switch allows students to choose using an optimized gate resistor or a potentiometer to observe the effect of different gate resistances on switching behavior.

C. Snubber Circuit Design

The snubber design was a challenge for both Si and SiC switches. The design of the snubber circuit is complicated because of the wide range of switching conditions seen by the MOSFETs. Several tests of different snubber topologies were conducted. An LTspice simulated circuit showed that the best snubber for this application was an RCD snubber as it minimized voltage spikes across the load and the switch. RCD snubbers induce power loss at higher power applications [16]. However, since this is an instructional board for which students will not be working with high power, this drawback is not a significant problem.

IV. Example Lab Demo

Before introducing PowerBox to the classroom, a lab manual will be drafted around this new board. This lab manual will cover the conventional circuits taught in introductory power electronics courses. In addition, new materials to show the differences between Si and SiC devices will be included. Below is an example of a lab centered around the implementation of Si and SiC into a Buck converter. Example lab instructions, as well as selected results that students can expect, are illustrated.

A. Lab Instructions

1) Lab Introduction

In this lab, students compare Si MOSFETs versus SiC MOSFETs as switches in a standard Buck converter. The lab aims to demonstrate the advantages and disadvantages of using SiC technology in power electronics circuits. This lab begins with constructing a Buck converter with standard Si switches. Students measure the input and output voltages, input and output currents, diode current and voltage across the switch at a duty cycle of 50% and a frequency of 10 kHz. Next, vary the duty ratio from 10% to 60% in increments of 10%, followed by changing to a switching frequency of 50 kHz. A similar process repeats with SiC switches, taking the same measurements as above.

2) Materials and Equipment

For this lab, students require the following:

1. PowerBox board
2. A breadboard with capacitors and inductors
3. Six banana cables
4. Variable load power resistors
5. Oscilloscope
6. Two differential voltage probes
7. Two current probes

3) Lab Instructions

Step 1: Connect the source terminal of Si MOSFET 1 on the PowerBox to the left terminal of the inductor on the breadboard and connect the cathode of Diode 1 to the inductor. Attach the anode of Diode 1 to the bottom of the capacitor on the breadboard.

Step 2: Connect the load resistor to the Buck board; place the load across Pins 3 and 4.

Step 3: Turn on the DC power supply and oscilloscope, while the DC power supply's output remains OFF. Connect the power supply to the PowerBox. The positive supply should connect to the drain of Si MOSFET 1, and the ground of the supply should connect to the anode of Diode 1. The supply is set to 20 V.

Step 4: Have a lab TA check off the circuit before turning on the PowerBox board and enabling the output of the DC power supply.

Step 5: Turn on the PowerBox and the DC supply output. Measure the voltage across Si MOSFET 1. Adjust the duty ratio until it is at 50% and ensure the frequency is set to 10 kHz. Measure and record the voltage across the switch, the source voltage and current, the load voltage and current, and the diode current. Remember to degauss any current probe before first usage. Use the oscilloscope to capture a picture of the voltage across the switch, as well as the current through the Diode.

Step 6: Repeat Step 5 for duty ratios of 10%, 20% 30%, 40% and 60%.

Step 7: Set the switching frequency to 50 kHz and the duty ratio back to 50%. Measure and record the voltage across the switch, the source voltage and current, the load voltage and current, and the diode current. Use the oscilloscope to capture a picture of the voltage across the switch, as well as the current through the diode.

Step 8: Repeat Step 7 for duty ratios of 10%, 20% 30%, 40% and 60%.

Step 9: Disconnect power and switch from Si to SiC. Then reconnect the load in the same orientation as before with the Si switch. Again, have a lab TA check off the circuit before turning on power.

Step 10: Turn on PowerBox and DC supply. Measure the voltage across SiC MOSFET 1. Repeat the remainder of Step 5.

Step 11: Repeat Steps 6 and 7.

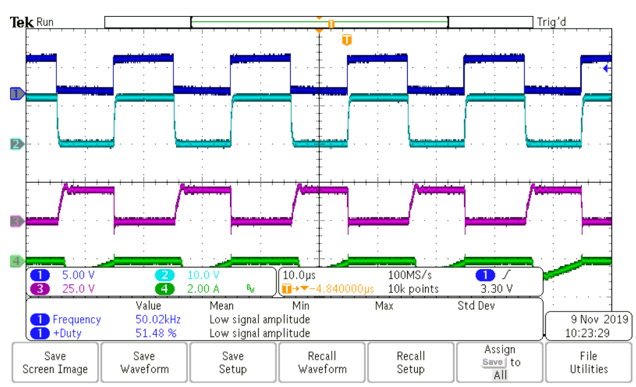

Figure 5: Si Buck converter waveforms at 50 kHz (Channel 1 = PWM; Channel 2 = Vgs; Channel 3 = Vds; Channel 4 = Id).

4) Post Lab Questions

Question 1: Attach the oscilloscope captures of the voltage across the switch (V_{ds}) taken with the Si and SiC switches. How do they compare? Is there any difference between the Si and the SiC waveforms at 10 kHz? What about 50 kHz?

Question 2: Attach the Diode currents captured for each switch. How do they compare between Si and SiC switches?

Question 3: Calculate the efficiency of the system at 10 kHz and the efficiency at 50 kHz for both switching technologies. How do the efficiency numbers compare at different frequencies? What about between Si and SiC switches?

B. Lab Hardware Demo

The PowerBox was wired with a Si MOSFET to form a DC-DC buck converter. We set the input voltage of the buck converter to 20 V DC, the duty ratio to approximately 50%, and the switching frequency of 50 kHz. We connected oscilloscope probes across the gate and source of the MOSFET (Channel 2), also measuring the drain to source voltage (Channel 3), PWM (Channel 1), and drain current (Channel 4). Figure 5 displays the oscilloscope waveforms of these measurements. Observe that the diode current goes to zero over one switching period, which indicates that the device is in discontinuous current mode (DCM). The onset of DCM can be attributed to the inductance being too small. The waveform of the drain to source voltage has a slight overshoot along with some oscillation when the switch turns off, given the discrete component wiring, which is unavoidable when students assemble the whole circuit. However, this ringing is truncated quickly due to the compact design of the layout and the snubber.

We then tested the same Si circuit with a switching frequency of 25 kHz and a duty ratio of 25%. Again, in Figure 6, there is a small overshoot in V_{ds} at turn off, along with some oscillation near the end of the on-cycle. This oscillation is much larger than what we saw with the waveforms for 50 kHz. Observe that the buck converter enters DCM, but for a much longer time due to the lower switching frequency. An increase in inductance can ensure that the system does not enter DCM.

Next, we focused on the SiC switch. The buck converter set up was identical to that using the Si switch. Again, we measured the drain current, drain to source voltage, gate to source voltage and PWM signal at 50 kHz with a 50% duty ratio (Figure 7) and 25 kHz with a 25% duty ratio (Figure 8). Note that the SiC MOSFET switches faster, under a similar gate resistance value. A similar voltage overshoot occurs in the drain to source

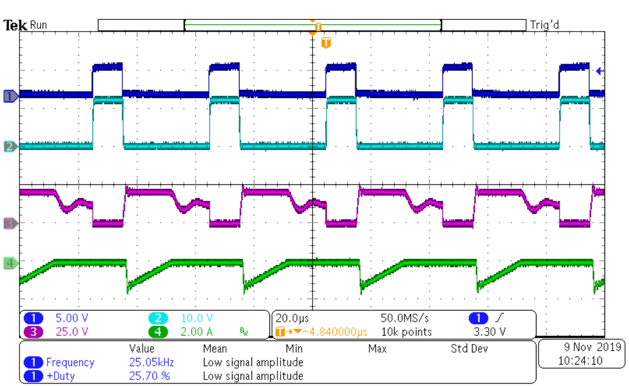

Figure 6: Si Buck converter waveforms at 25 kHz (Channel 1 = PWM; Channel 2 = Vgs; Channel 3 = Vds; Channel 4 = Id).

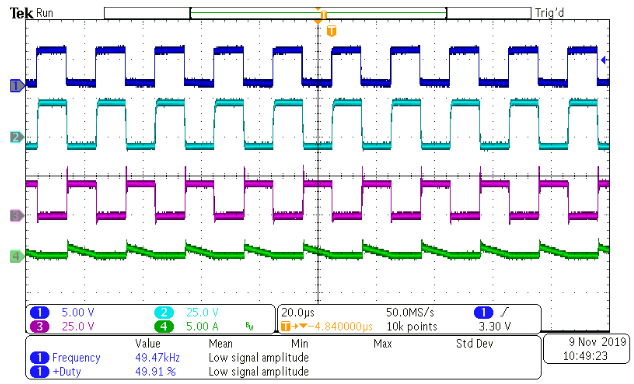

Figure 7: SiC Buck converter waveforms at 50 kHz (Channel 1 = PWM; Channel 2 = Vgs; Channel 3 = Vds; Channel 4 = Id).

voltage, though slightly more substantial. The oscillation is decreased compared to the Si experiment.

In Figure 8, we obtained similar switching characteristics in the 25 kHz waveform. We observed a larger turn off voltage overshoot. The oscillation in near the end of the off-cycle occurs again with the SiC switches, though note that this oscillation is of a different frequency than what we observed with the Si switches.

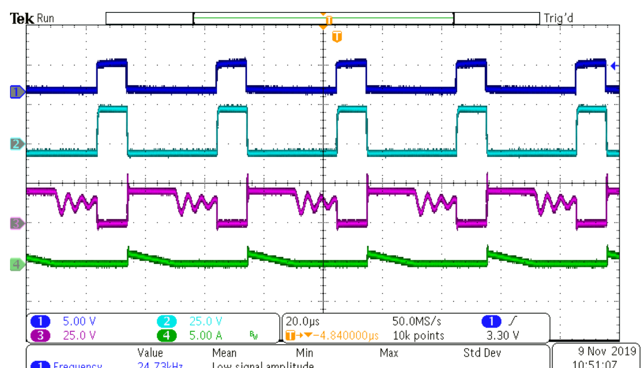

Figure 8: SiC Buck converter waveforms at 25 kHz (Channel 1 = PWM; Channel 2 = Vgs; Channel 3 = Vds; Channel 4 = Id).

V. Overall Comments and Future work

When compared with the other boards, the designed PowerBox falls into a middle ground among several metrics. The board exceeds the Minnesota Vishay Dale board in the number of applications and is on par with the Illinois Blue Box. The new PowerBox features the ability to be used in any basic DC-DC converters, half- and full-bridge AC-DC rectifiers, and half-bridge DC-AC inverters. The selection of semiconductor technology allows students to switch between Si and SiC in an efficient and user-friendly manner. In terms of pricing, PowerBox is more expensive than the Illinois Blue Box but cheaper than the $1,700 (Priced from Digikey) Minnesota /Vishay Dale power pole board. The PowerBox is 33% larger than the Blue Box (11.83 inches by 5.00 inches vs. 8.13 inches by 5.5 inches) because of the inclusion of both Si and SiC modules, but still smaller than the Vishay Dale board.

Before a final revision of the PowerBox is produced, we aim to increase the functionality and usability of the board. We have found that a common point of failure in the board is the digital isolators that lead to the silicon drive circuitry. This fault can be negated by replacing the isolators with a more robust component. This revision also offers an opportunity to decrease the total part count and cost if an isolated gate driver IC is implemented. Another possible point of failure is the Murata DC-DC converter used for the SiC gate drive circuitry, which has shown to be unreliable. The snubber and gate drive circuitry may also be improved further to reduce the amount of oscillation and voltage overshoot during the turn off cycle of the drain to source voltage for both Si and SiC MOSFETs.

A mechanical enclosure will be constructed to accompany the final product. This enclosure will feature labeled interfaces for increased usability, industry-standard power connectors, cooling fans, and LEDs to inform on/off conditions at various places as well as to notify current operation mode (Si or SiC). A webpage featuring downloads for the schematics, board layout, enclosure, bill of materials, laboratory procedures, and other necessary information will also be developed.

VI. Conclusion

This paper discusses the design of a new power electronics teaching board, namely PowerBox. This new instructional board features many advantages when compared to older boards. Due to its similarities to the Illinois Blue Box, the PowerBox can be implemented into DC-DC, AC-DC, and Half-Bridge DC-AC laboratories within an educational course. It also allows for the implementation of the Blue Box method of instructional laboratories. Where the PowerBox begins to separate from earlier boards is the new technologies that are present within the circuit board. The most obvious advantage is the SiC devices that are included among the other modern ICs and semiconductor devices. A less obvious boon that these devices offer is their decreased size, which allows for a smaller system and in turn, lowers costs of manufacturing. Along with this, the implementation of an adjustable gate resistor allows for students to become more familiar with the impact of a gate drive circuitry. The paper discussed the design philosophy, along with several difficulties that occurred during the creation of the board. An example lab is demonstrated, and plans for future updates are laid out.

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APPENDIX

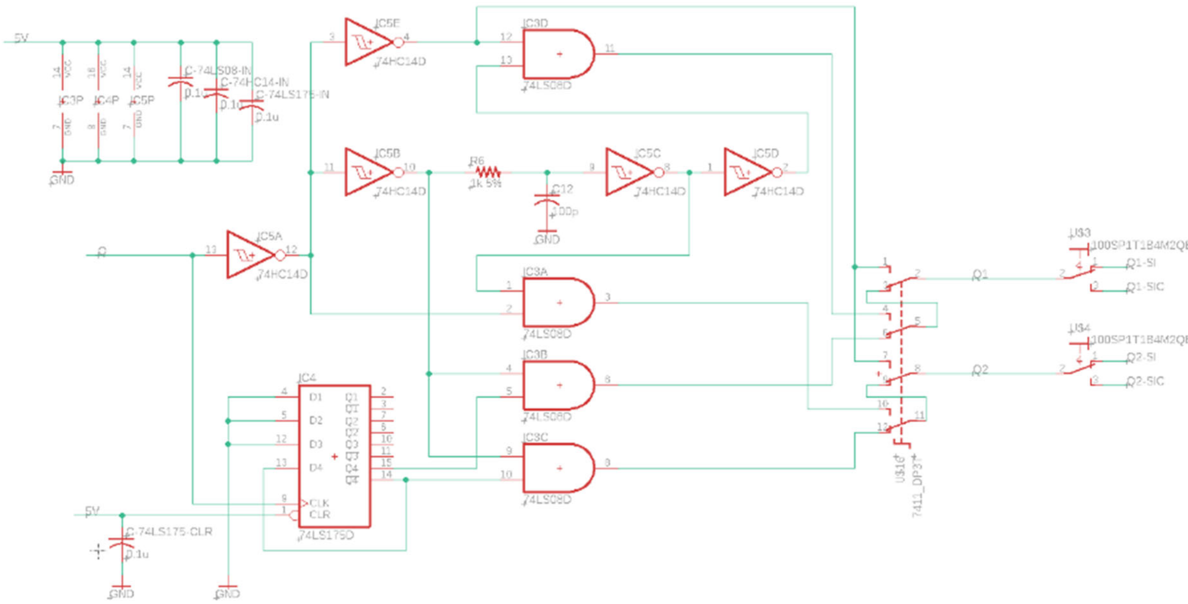

Figure 9: PWM logic circuit schematics.

Table 1: List of parts.

Device	Description	Quantity
1SMA5917BT3G	Zener Diode	2
1SMA5918BT3G	Zener Diode	1
1SMA5927BT3G	Zener Diode	1
1SMA5932BT3G	Zener Diode	1
3310Y-001-502L	5k Potentiometer	3
3310Y-001-503L	50k Potentiometer	1
74HC14D	Schmitt Trigger Inverter	1
74LS08D	Quad 2-Input AND	1
74LS175D	Quad D Flip-Flop	1
7805T	5 V Regulator	1
DSEI30-06A	Power Diode	8
IPW60R040CFD7	Si MOSFET	2
ISO7320FCDR	Digital Isolator	2
MCP14A0602	Gate Driver	3
MUR160	Diode	2
MURS360	Diode	2
SLC03A-12	12 V DC-DC Converter	2
UC3526DW	PWM Controller	1
UCC5320ECDR	Isolated Gate Driver	2
MGJ6D122005DC	20V/-5V DC-DC Converter	2
SCT2160KEC	SiC MOSFET	2
Assorted Resistors and Capacitors		