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EFFECT ON CHARGING EFFICIENCY USING GALLIUM NITRIDE DEVICES

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ABSTRACT

Electric vehicles (EVs) and hybrid electric vehicles (HEVs) were created to lessen our dependence on natural resources. EVs and HEVs run on battery packs and the pack can be recharged from a household outlet. Because the vehicles are charged using energy draw from the grid, the problem of efficiency on a large scale become a concern. For conventional chargers, the charging efficiency may be improved due to enhanced in battery technology, charging protocol, or charging circuitry. Recently, Gallium Nitride (GaN) devices were introduced that have better performance than other semiconductors used in charging circuits. GaN has a higher bandgap than conventional materials which allows it to withstand high level of voltage. GaN can also operate at higher frequency resulting in much faster switching capability. The ability to withstand higher temperature allows GaN devices to require smaller heat sinks which effectively reduce the cost of the devices. In this thesis, a DC-DC converter as used in battery charger will be designed using Gallium Nitride devices and tested for efficiency. The results will be compared with a converter using conventional Silicon components. The results can then be projected to higher voltages and currents. Further study and testing should be applied to chargers used in electric vehicles or hybrid electric vehicles.

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Chapter 1: Introduction

Electric vehicles and hybrid electric vehicles were developed to lessen our dependence on natural resources i.e., gasoline. As technology develops, more advanced models of electric vehicles have been introduced. Electric battery chargers working off the power grid are used to recharge the batteries in electric vehicles and plug-in hybrids. As of today, there are two types of electrical vehicle chargers in common use. Level 1 chargers uses the standard 120 V AC from a standard residential or commercial outlet to charge the battery, and can be used virtually anywhere in the US. Level 2 chargers run on 240V AC, which requires a dedicated outlet from most residential and commercial structures, but is more widely available in industrial settings. Level 2 chargers generally have better efficiency than level 1 chargers because they draw less current, and incur less voltage loss in the wiring leading to the charger. According to a report by Vermont Energy Investment Corporation, an average level 2 charger has 86.4% efficiency, compared with 83.7% for level 1 charger [1]. However, for low energy charging (less than 2kWh drawn from the grid), the efficiency of level 2 chargers drops to 83.5% and that of level 1 drops to 70.7% [1]. This leaves potential room for improvement.

According to Energy Policy Information Center, more than 220,000 plug-in vehicles have been sold in the U.S between 2011 and 2014 with 80% of all sales dominated by Chevrolet Volt, Nissan Leaf, Tesla Model S, and Toyota Prius [2]. A sample calculation illustrates the benefit of improved charging efficiency. Table 1 shows the sales of Nissan Leaf, Chevy Volt, and Tesla Model S in 2014.

Table 1. EVs Sales in 2014 [3]

Type	Sales in 2014
Nissan Leaf	21,822
Chevy Volt	14,540
Tesla Model S	11,000

The battery capacity of the Chevy's Volt, Nissan's Left, and Tesla's Model S are 17.1 kWh, 24 kWh, and 60 kWh respectively. Assuming each type of car was charged with 2 chargers operating at 80% and 85% efficiencies, then the energy savings for one single charge (from empty to full) is shown in Table 2.

Table 2. Estimated power saving when efficiency is improved by 5%

Type	80% Efficiency	85% Efficiency
Chevy Volt	466.4 MWh	439 MWh
Nissan Leaf	436.2 MWh	410.5 MWh
Tesla Model S	825 MWh	776.5 MWh
Total Energy Consumed	1727.6 MWh	1626 MWh
Saving	101.6 MWh	

This energy saving in the State of California alone may be estimated. The average electricity price in California is approximately 17.36 cents/kWh [4]. With the saving of 101.6 MWh, Californians could potentially save about $17,600 in electric bills over a single charging cycle.

The charging protocol is determined by the type of battery, the amount of voltage and current to be applied, time required for a full charge, and the limitations of the electronic circuitry of the charger. Currently, Lithium-ion batteries are chosen as the most popular power source for electric vehicles and hybrid electric vehicles because they can hold the most charge for their size and weight. They have the highest capacity compared with all other types of rechargeable batteries on the market. For charging Lithium-ion batteries, there are two main charging protocols in common use. The conventional method is constant current/ constant voltage charging (CC/CV) where the battery is charged by a constant current until its voltage reaches a certain level and then switches to constant voltage to top off the charge. The other method is pulse charging where the battery is charged by delivering the current or voltage in discrete pulses to the battery. The pulse charging method is generally regarded to be more efficient than the CC/CV protocol [5] because it provides a rest period between pulses for the ions in the battery to diffuse and redistribute and thus reduces buildups that could lead to poor efficiency, heat generation, reduced charge capacity, and shortened life span [6]. Much work has also been done on the design of electronic circuits to improve efficiency. The main function of the electronic circuit is to convert the AC power from the outlet to the appropriate DC or pulsed power that will charge the battery. To achieve high efficiency, the circuit has to be able to convert and transfer the power with little to no internal power loss. One nice example of such a high-efficiency step-down converter was recently published by Chuang and Ke [7].

Most research in high-efficiency battery chargers has focused on two areas -

refinement of circuit designs and development of electronic components with superior specifications for internal loss, operating speed, current and voltage capability, and better thermal properties. Most of today's chargers make use of power semiconductors to switch and regulate charging current and voltage. Silicon devices predominate, with Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) demonstrating the best performance in switching and power transfer capabilities. Only recently, Field- Effect Transistors (FETs) made of Gallium Nitride (GaN) have been introduced as an alternative that offers better performance than conventional silicon power MOSFETs, with higher voltage capability, higher frequency, and higher temperature tolerance than conventional Si power MOSFETs [8]. The eGaN transistor produced by Efficient Power Conversion Corporation has similar characteristics to power MOSFETs, but with improved high speed switching, lower internal resistance, and smaller size that would be able to reduce power loss and improve efficiency in battery charger applications of power delivery systems.

The objective of this Honors project is to investigate whether or not GaN transistors can improve the power transfer efficiency of battery chargers for electric vehicles. While time and cost constraints will preclude testing of chargers for actual electric vehicles, I plan to pursue this research with a scaled-down DC-DC converter, which is similar in principle and operation to a full-scale vehicle's battery charger. My thesis will focus on answering the question: "Can Gallium Nitride transistors improve the efficiency of DC-DC converters used in battery charging application?".

Chapter 2: Literature Review

Electric vehicles (EVs) and hybrid electric vehicles (HEVs) are becoming more popular due to the growing concern for the environment and consumption of fossil fuel. As of today, the main approach to charge EVs and HEVs is by drawing power from a charging station or from an outlet at home. A charger is designed for the purpose of converting the AC power from an outlet to an appropriate DC power level of the battery. An efficient charger can reduce the burden on the utility system by only drawing enough power to charge the battery. The Gallium Nitride transistor technology could be used to improve the charging efficiency of the charger. This section will review such technology as well as other aspects that need to be considered in order to design an efficient charger.

2.1. Gallium Nitride Transistor Technology:

Before the development of Gallium Nitride (GaN) devices, there were three types of transistors that were frequently implemented in power supply design. The Bipolar Junction Transistor was the first to see widespread use due to its high current and voltage capacity. With the advent of VLSI technology, power MOSFET became prominent in the 1970's, and replaced power BJTs due to their inherent noise immunity, ease of driving, and lower internal resistance. In addition, unlike BJTs, MOSFETs can be "ganged", arranged in parallel to multiply their current capacity and divide their internal resistances. Furthermore, MOSFETs have a body-drain diode to prevent back-feeding current from inductive components in the system. Since then, IGBT's (Insulated Gate Bipolar Transistors) have been developed as a hybrid between MOSFETs and BJTs that offer the best of both worlds for higher power applications [9].

Gallium Nitride (GaN) devices are on the rise in the semiconductor world due to their ability to withstand higher temperatures and operate at higher frequencies and power levels higher than silicon (Si), as well as others, including Gallium Arsenide (GaAs) and Silicon Carbide (SiC). Compared to the Si, GaAs, and SiC, GaN has a higher voltage rating before break down, and higher electron mobility, affording faster and easier electron flow. These advantages allow for the realization of high speed, high voltage, and high temperature switching devices such as transistors. Table 3 shows the comparison between the characteristics of GaN material and other semiconductor materials.

There has been ongoing research to investigate the capabilities of GaN transistor, some of which has produced some amazing results. Research teams at Cornell University and the University of California at Santa Barbara reported fabricating GaN transistors capable of sustaining power densities above 10W/mm of gate width, while amplifying signal at 10 GHz [10]. Researchers at Astralux tested a GaN transistor at 300^{o}C of ambient temperature and found that it can amplify an AC signal by a factor of 100 [10]. GaN's ability to operate at high temperature without degradation in its performance would enhance the GaN devices' ability to work in applications with harsh temperature condition or reduce the size of heat sink in more conventional applications. High electron mobility allows GaN devices to work at higher frequency which could reduce the size of passive components such as filter inductors and capacitors [11]. The high breakdown field of GaN also allows the devices fabricated from GaN to operate at higher voltage. The higher voltage would result in higher power density which allows manufacturers to reduce the physical size of the GaN devices and allow them to supply more power.

Table 3. Comparison between GaN and other semiconductor materials [10].

Semiconductor (commonly used compounds)		Silicon	Gallium arsenide (AlGaAs/ lnGaAs)	Indium phosphide (lnAlAs/ lnGaAs)	Silicon carbide	Gallium nitride (AlGaN/ GaN)
Characteristic	**Unit**					
Bandgap	**eV**	1.1	1.42	1.35	3.26	3.49
Electron mobility at 300 K	**cm^2/Vs**	1500	8500	5400	700	1000-2000
Saturated (peak) electron velocity	**$x10^7 cm/s$**	1.0 (1.0)	1.3 (2.1)	1.0 (2.3)	2.0 (2.0)	1.3 (2.1)
Critical breakdown field	**MV/cm**	0.3	0.4	0.5	3.0	3.0
Thermal conductivity	**W/cmK**	1.5	0.5	0.7	4.5	>1.5
Relative dielectric constant	**ε_r**	11.8	12.8	12.5	10.0	9.0

Although GaN material has many advantages over other semiconductor materials, there are some difficulties in manufacturing GaN based devices for several reasons. Fundamentally, there exists no inexpensive material to make the substrate for gallium nitride. The substrate is the foundation of the semiconductor upon which layers of circuitry and interconnections are subsequently built. A mechanically and thermally stable device has its substrate and its active components made of materials that are structurally and thermally compatible. Different materials have different thermal coefficient of expansion (TCE). The stress created by TCE mismatch would degrade the performance and reliability of the device. The substrates are wafers that are cut from monocrystalline cylinders called boules [10]. More research is needed to understand how to grow boules of gallium nitride. Therefore, most GaN devices are fabricated on other materials that have the lowest mismatch with it such as sapphire (14.8%) or silicon carbide (SiC) (3.3%) [10]. A constraint for using this method is that the cost to fabricate these substrates is very high. A 50 mm wafer of GaN on SiC can cost about $10,000 which is far more expensive than prepared silicon wafers, which are regularly fabricated in much larger size [10].

In 2004, the Depletion mode High Electron Mobility Transistor (HEMT) gallium nitride transistor was fabricated using GaN on a SiC subtrate by Eudyna Corporation in Japan. In 2005, Nitronex Corporation introduced their first depletion mode HEMT transistor using silicon as substrate that could reduce the cost of producing GaN transistors. Most of the application was focused on Radio Frequency (RF) operation. Other applications outside of this field have been limited by either the device cost or the inconvenience of depletion mode operation [8].

In 2009, Efficient Power Conversion Corporation (EPC) introduced their first enhancement mode GaN on Silicon (eGaN). This transistor is designed to replace silicon power MOSFETs in power conversion application. An enhancement mode device is normally off and must be supplied a gate voltage to turn on while depletion mode is the opposite, the device is normally on and must be supplied a negative gate voltage to turn off. Therefore, depletion mode was inconvenient in power conversion because at the startup of the power converter, a negative voltage must be applied to the power device or a short-circuit will occur. While in enhancement mode, the device is normally off at zero bias and would not suffer that limitation [8]. The eGaN transistors have similar characteristic to power MOSFET, but with improved high speed switching, low on-resistance, and smaller size. With these new characteristics, the eGaN transistor would be able to reduce power loss to improve efficiency in power conversion system [8].

2.2. Batteries:

Because different batteries have different materials and electrochemical bases, one must understand the operation of each type of battery before designing a charger. A battery is an electrochemical device that has the ability to convert chemical energy into electrical energy. Rechargeable batteries are different from single use batteries as their electrochemical reactions are electrically reversible, meaning they can take electrical energy from an outside source to restore their state of charge. Demand for rechargeable batteries has risen due to the development of portable devices such as cell phones, laptop computers, and other personal electronic devices. Rechargeable batteries are also an important component in EVs and HEVs. This section will discuss two types of rechargeable batteries that are popular in EVs and HEV applications which are Nickel Metal Hydride (NiMH) and Lithium-ion (Li-ion).

2.2.1. Nickel Metal Hydride Batteries:

Nickel metal hydride (NiMH) batteries were developed in 1989 and were commercialized in Japan in 1990. They were intended to replace Nickel-Cadmium batteries because of the environmental risks associated with their Cadmium content. NiMH batteries usually comprise of a porous Ni plate with nickel hydroxide as the positive electrode, a hydrogen storage alloy powder such as Mn-Ni-Co as the negative electrode, and potassium hydroxide as the electrolyte [12]. They are popular in both consumer and industrial applications due to many features such as flexible cell capacity ranging from 30 mAh to 2500 mAh, safe operating at high voltage (over 300 V), tolerance to overcharge and over discharge, as well as being more environmentally friendly [13]. Depending on the application, the specific energy of NiMH battery can vary between 40 and 110 Wh/kg (Wh/ kg is the energy the battery can store relative to its weight). The specific energy is about 90-110 Wh/kg for consumer application, 65-80 Wh/kg for EV batteries, and 45-60 Wh/kg for HEV and other high power applications [13]. Figure 1 shows the improvement in specific energy of NiMH battery from 1991 to 2006. Energy density is also an important factor in batteries because it represents the energy that the system can store relative to size and weight. NiMH has exceptionally high energy density of up to 420 Wh/l.

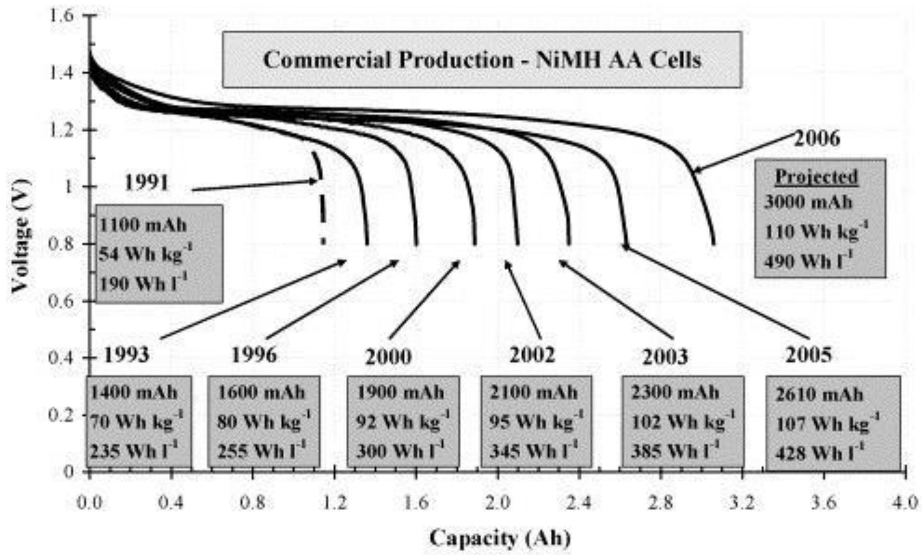

Figure 1. Improvement of NiMH specific energy [13].

One important feature of NiMH batteries is the ability to tolerate overcharge and over-discharge that could lead to a buildup of pressure inside a sealed cell and damage it. This feature is advantageous for electric vehicle batteries where many individual cells are connected in series and would be subjected to various degrees of charging and discharging. The ability to tolerate overcharging and over-discharging eliminates the need for voltage monitoring and therefore simplifies the battery system [14].

Ovonic is the first company to produce NiMH battery for electric vehicle application. An Ovonic NiMH battery pack was first tested in the state of the art GM Impact vehicle in January 1994. A range of 200 miles with acceleration from 0 to 60 m.p.h in under 8 seconds was demonstrated. Ovonic batteries are resistant to physical abuse such as short-circuit, prolonged high rate overcharge and over-discharge, puncture, crush, drop, etc. A key advantage to Ovonic NiMH batteries are their long cycle life. A result of over 600 cycles was achieved at 80% depth of discharge under Dynamic Stress Test for EV cells. This would be equivalent to 96000 miles of driving with an average range of 200 miles per charge [14].

There are many factors that affect the performance of the battery. Temperature is one such factor. While in operation, NiMH batteries are subjected to the effect of heat generated by the batteries themselves. In temperature exceeding 50^{o}C, the charging efficiency and battery life may deteriorate. Sato and Yagi (2000) analyzed the thermal behavior of nickel metal hydride reaction during charging and discharging [15]. They concluded that heat generation of the battery is directly related to performance, management technology, and energy efficiency, and thermal management technology is regarded as the first factor for studies of new material and design of battery. Extensive work has been done on the positive electrode to improve charging efficiency over a wide temperature range. Fetcenko (2007) tested different powder compositions that could improve the charge acceptance of the positive electrode [13]. These powders composition were shown in figure 2. The results showed the cobalt rich, zinc poor powder containing calcium and magnesium could improve the charge efficiency at higher temperature.

Powder	Cationic hydroxide composition	X-ray FWHM 〈1 0 1〉	Particle size (um)	Tap density (g cc^{-1})	BET surface area (m^2 g^{-1})
Powder A	$Ni_{91.3}Co_{2.4}Zn_{5.7}Ca_{0.5}Mg_{0.1}$	1.02	12.0	2.15	16.5
Powder B	$Ni_{91.0}Co_{4.5}Zn_{4.5}$	1.05	10.8	2.20	12.8
Powder C	$Ni_{85.5}Co_{7.0}Zn_{6.0}Ca_{1.0}Mg_{0.5}$	0.88	8.3	2.19	17.8
Powder D	$Ni_{91.0}Co_{7.0}Zn_{0.5}Ca_{1.0}Mg_{0.51}$	0.93	9.8	2.2	10.6

Figure 2. Different powder composition for NiMH positive electrode [12].

2.2.2. Lithium-ion Batteries:

Lithium ion batteries are light, work with a voltage of the order of 4 V with specific energy ranging from 100 Wh/kg to 150 Wh/kg and 650 Wh/l [16, 17] with lifetime of over 500 charge / discharge cycles. Along with high energy density, Li-ion batteries can be fabricated in a size from a few microns to a large scale battery which make them favorable as storage device in portable electronic devices as well as electric vehicle applications. Compared to NiMH batteries, Li-ion batteries have higher energy density. Figure 3 shows the energy density per unit volume and per unit weight of various rechargeable batteries in 2001. However Li-ion batteries are sensitive to overcharge and over-discharge and therefore would require extra circuitry to protect the batteries from such conditions.

Conventional Li-ion batteries comprise of a graphite anode, a lithium metal oxide ($LiMO_2$ or $LiCoO_2$) cathode, and liquid, carbonate electrolytes [17]. However, due to various incidental fires caused by the released of oxygen from the layer of $LiCoO_2$ and by the instability and flammability of the liquid organic electrolytes, a solution of a lithium salt ($LiPF_6$) in a mixed organic solvent was used as new electrolyte for the battery [16, 17].

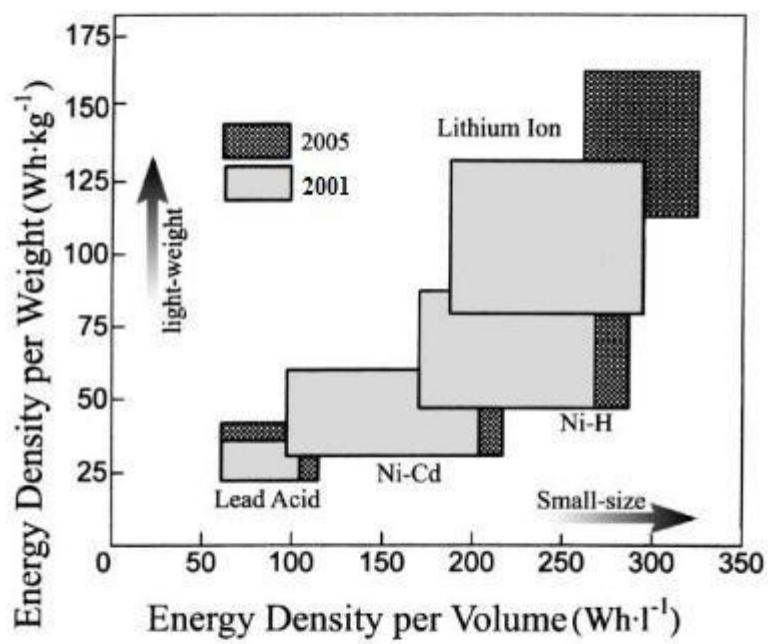

Figure 3. Energy density of rechargeable batteries [18].

Much research has been done to improve the performance of Li-ion batteries. In [16, 17, and 18] , the authors explored different materials that could be used to improve specific energy, power, safety, and reliability of lithium ion batteries as well as their limitations such as slow electrode kinetic (how fast an electron can be transferred when voltage is applied) and large volume expansion-contraction upon cycling. They concluded that the batteries' performance clearly depends on the electrode and electrolyte performance. The performance can be enhanced or modified by optimizing their morphology while the limitations can be circumvented by switching to nanostructures. In addition, nanostructure can change the reaction pathway and affect capacity, power, and reversibility positively [16].

Like the problem of NiMH batteries, temperature from self-heating also affects the performance of lithium ion batteries greatly. For different battery systems, exothermic behavior can vary greatly. Therefore, thermal management must take into account battery reaction and thermal generation factors. Sato (2001) analyzed the thermal behavior of lithium ion batteries from a thermodynamic perspective [19]. The analysis was verified by confirming the correspondence between simulation results and actual measurements. It was concluded that thermodynamic analysis of batteries reactions permitted the categorization of the specific heat generation factors and the estimation of a battery's exothermic properties. From the paper, the proper approach to thermal management for Li-ion batteries could be determined. It is important to consider all of these battery's characteristics in order to select the most efficient way to charge the battery.

2.3. Power Converter:

For plug-in hybrid electric vehicles or electric vehicles where the battery is charged by drawing power from an external outlet, the power must be converted to a appropriate type and power level to charge the battery. There are two steps in charging a battery. First, the AC outlet voltage is rectified into DC voltage. Then, that DC voltage is then converted to the voltage level that works best for charging the batteries depending on their specification and arrangement in series or parallel. This section will discuss different topologies for AC-DC and DC-DC converter.

2.3.1. AC-DC Converter:

An AC-DC converter or rectifier is used to convert an AC signal to a DC signal. Figure 4 shows a full wave bridge rectifier circuit that converts AC to DC, and a smoothing capacitor to reduce the voltage ripple on the DC output. Conventional rectifiers are inexpensive and widely used. However, such converters are undesirable in application of HEVs and EVs because they introduce phase shift and waveform distortion of the charging current, resulting in a reduction in power factor and increased higher harmonic content. Low power factor wastes power and places a burden on the utility system, while harmonic distortion can have a negative effect on other components of the system [20].

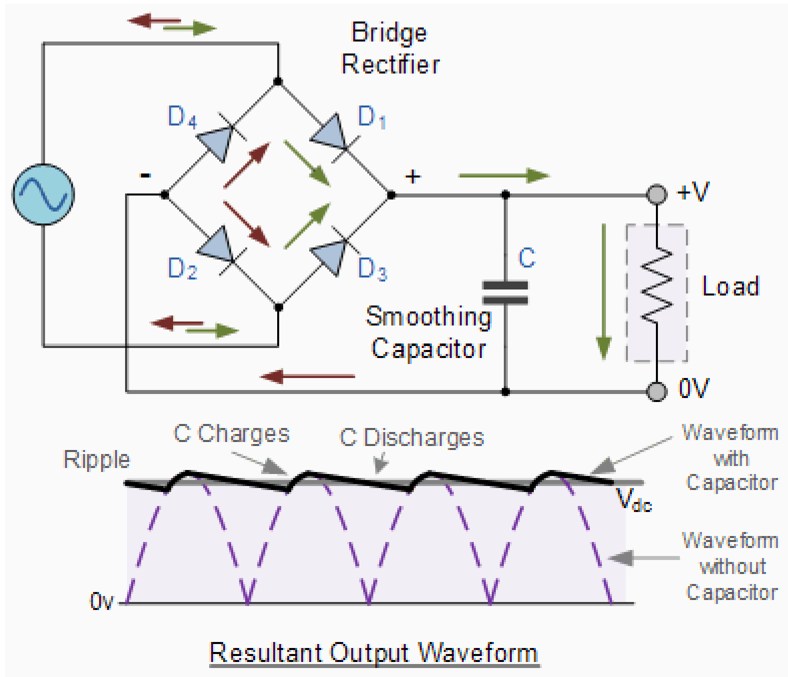

Figure 4. Full wave bridge rectifier with smoothing capacitor.

To overcome the problem, a Power Factor Correction (PFC) based AC-DC converter is desirable [21]. Because a line voltage is not distorted, the PFC is designed to force the line current to match the waveform of the line voltage. This causes an imbalance between the instantaneous power between the input and output power. Therefore, the PFC must process the signal so that it stores the excess input energy when the input power is larger than the output power and releases that energy when the input power is less than the output power. In simple term, an energy storage element such as capacitor must be included in the PFC circuit.

For most PFC circuits, an input inductor is used in series with the bridge rectifier to smooth out the line current. The inductor can operate in continuous conduction mode (CCM) or discontinuous conduction mode (DCM). DCM circuits are more beneficial than CCM in term of power factor. However, the inductor operating in DCM cannot hold the excessive input energy because it must release all of its stored energy before the end of each switching cycle. Therefore, a large capacitor is used to balance the instantaneous power between the input and output. Also, when the DCM is implemented, the input current takes on a triangular waveshape, and needs an input filter to smooth out the input current [21]. Wei and Batarseh (2000) proposed a single state single switch ac-dc converter using a DCM boost circuit as an input stage to perform PFC and a forward circuit as an output stage. The circuit was designed to overcoming the difficulties in constructing an effective single stage single switch AC-DC converter such as leakage inductance, limited capabilities, increased cost, and distorted line current. Experimental results showed that a high power factor and efficiency of 99% and 87% respectively for 110V operation were achieved [21]. For 220V operation, the power factor and efficiency were 95% and 81% respectively [21].

2.3.2. DC-DC Converter:

There are different topologies for DC-DC converters. However, this section will only discuss step down DC-DC converters, which reduce a higher DC voltage to a lower DC voltage. The buck converter has been widely adopted for step down DC-DC conversion. However, buck converters have a narrow range of duty cycles, which limits its application for high step down DC-DC conversion. In high step down dc-dc conversion, the voltage gain is very small and so the duty cycle becomes small as well. Consequently, the conduction angle is very short, this makes it difficult for the switch to turn fully on or off in a short period of time. Figure 5 shows the circuit for a synchronous buck converter. The efficiency of synchronous buck converter operating at small duty cycle is low. There are also the problems of conduction loss and body diode recovery loss associated with the bottom switch MOSFET [22]. To avoid the small duty cycle, different topologies are proposed that use a transformer to control the duty cycle. However, these topologies are complicated and difficult to implement. Yao and Ye (2005) proposed a method to overcome the above mentioned problems while keeping the simplicity of the buck converter circuit. The method implemented a tape inductor (TI) buck converter with a slight modification of the buck converter circuit. The result indicated that the T1 buck converter improved efficiency by extending the duty cycle while maintaining the benefits of simple structure and low cost.

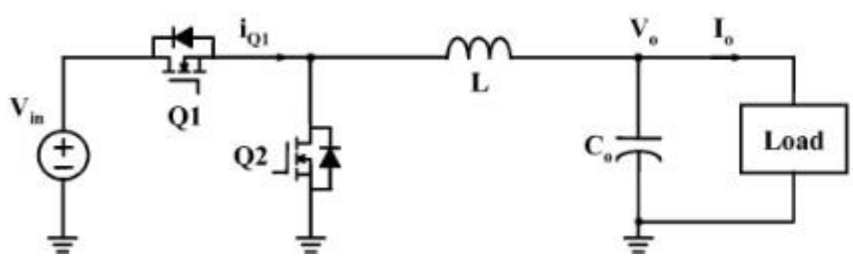

Figure 5. Synchronous buck converter.

Another method that is used in power conversion is Pulse Width Modulation (PWM). PWM method is used to control the switching of power devices to produce an output voltage. The PWM method regulates the time a switch switches on and off by setting the switching frequency of an active power switch. Consequently, the output voltage is controlled by varying the pulse width of the trigger signal on the power switch. Simply put, PWM method varies the duty cycle of the device to control the voltage. However, traditional PWM converters have switching losses associated with the voltage and current in the switching devices. The switching loss increases as the switching frequency increases. Figure 6 shows the switching loss in traditional PWM operation.

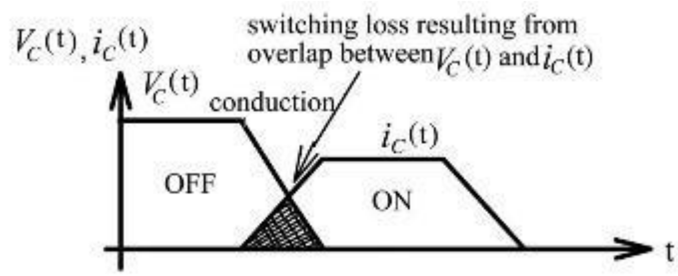

Figure 6. Switching loss in traditional PWM power switch [7].

Various methods were developed to eliminate the switching loss. One such method is resonant switching. By inserting a resonant tank such as a combination of capacitor and inductor, resonant switching works by forcing the switch current to zero before the transistor turns on or off. The advantage of the resonance converter is that reducing the voltage or current on the power switch to zero decreases the switching loss from the power switch. However, the voltage or current sinusoidal wave resulting from the resonance circuit increases voltage/current stress on other components. To overcome the problem, soft switching techniques were created. Soft switching power converters can be classified into zero voltage transition (ZVT) or zero voltage switching (ZVS) and zero current transition (ZCT) or zero current switching (ZCS). ZVS operates by implementing a clamp switch in the converter design. The purpose of the clamp switch is to reduce the voltage between the drain and source of the main power switch to zero during turn on transition which effectively eliminates any loss during the on time of the main transistor. ZCS works by the same principle but the current is reduced to zero during the off time of the main switch. By implementing such techniques, the switching loss and voltage/current stress are both reduced. Figure 7 shows the switching loss in a soft switching ZVT power switch.

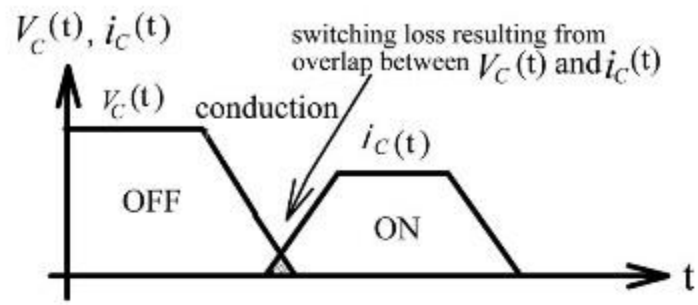

Figure 7. Switching loss in a soft switching ZVT power switch [6].

Various topologies employing soft switching technique were developed to improve charging efficiency in battery charger system [7, 23]. Chuang and Ke (2008) proposed a ZVT-PWM soft switching buck converter topology for a battery charger. They found that the resulting charging efficiency was 90.1 % and operated at lower temperature when compared to the traditional PWM switching converter [7]. Similarly, Chuang (2010) proposed a ZCT-PWM buck converter and found a charging efficiency of 90.3% [23].

2.4. Charging Method:

Battery charging systems have been intensively researched ever since the invention of rechargeable batteries. A charger has the following functions: delivering charge to the battery, optimizing the charge rate, and terminating the charge. The charge can be delivered to the battery through different charging techniques such as constant current (CC), constant current/constant voltage (CC-CV), or pulse charging. Pulse charging is considered to be optimal because it improves charging speed and efficiency [6]. The charge rate can be optimized if the capacity and state of charge are given. One example is trickle charging to keep the battery from being damaged when it is completely discharged or sustain the full charge state when it is fully charged. For charge termination, different techniques are used such as monitoring the temperature or voltage of the battery. Because each battery system is different, the charging algorithms are also found to be diverse. Hussein and Batarseh (2011) reviewed different charging algorithms for different batteries including the strengths and limitations of each algorithm [24].

The CC-CV charging method is widely used today because it has lower cost and simple design [6]. However, the charge speed and efficiency of the CC-CV charge strategy is still too low to satisfy users' requirements. It takes about 25% - 40% of the complete charging period to fulfill about 75% - 80% of the totally required charge capacity during the CC mode, and the time to fill the remaining 20% - 25% capacity during CV mode is 3 times as long in the CC mode [25]. Therefore, advanced control techniques such as fuzzy control, artificial neural networks, and genetic algorithms were developed to increase the charger performance. These advanced charge methods have been explored because they can adapt to nonlinear characteristics, and can reach the ultimate charge performance. Hsieh and Chen (2001) proposed a fuzzy control active state of charge controller (FZ-ASCC) to replace the CV mode in order to reduce the charging time [25]. The proposed FC-ASCC can instantly monitor the charging state of the Li-ion battery for adaptively programming its charging performance. They concluded that the proposed method can improve the charging performance about 23% when compared with the general CV mode.

However, the battery charge performance can still be increased through consideration of electrochemical characteristics. The pulse charge strategy was developed that could increase the battery life cycle and reduce the battery charge time. This technique relies on providing a pulse current to the battery for up to one second followed by a rest period of no charge lasting for milliseconds [6]. That rest period provides time for the ions to diffuse and neutralize, thus reducing a buildup that could lead to poor efficiency, heat generation, lower capacity and shortened life span. However, there is no method to determine the suitable rest period at the present. In fact, the duty cycle in commercial battery pulse charge systems is usually determined by trial and error or empirical method. Chen (2009) proposed a duty cycle varied voltage pulse charge strategy (DVVPCS) to overcome the aforementioned problem [5]. The proposed DVVPCS can detect the suitable pulse charge duty and supply the suitable charge pulse to the battery to increase charge speed and charge efficiency. He found out that the charge time of the proposed method was improved by 14% when compared to the standard CC-CV charge method and 5% when compared to the fixed 50% duty cycle pulse charge method. The charge efficiency was also improved by about 3.4 % and 1.5% respectively.

Other than the CC-CV and pulse charging methods, there is another charging method called reflex charging. This charging method is a variation of the pulse charging method. The reflex method provides high pulse current to charge the battery which improves the charging time followed by a negative pulse discharging current and a rest period that could relax the reaction of electrolyte and extend the battery life [26]. Li and

Murphy (2001) analyzed the effect of reflex charging method on commercial Li-ion batteries [27]. They found that pulse charging eliminates the concentrated polarization which allows the active material to be completely utilized. The charging time was shortened and battery life was prolonged. The charging time was about 180 minutes for the reflex method while it was 300 minutes for CC-CV method. The battery life was also improved from 700 cycles for CC-CV to 1200 cycles for reflex charging.

Chapter 3: Methodology

Most of today's EVs and HEVs are charged using plug-in method that draws power from an outlet using a battery charger. However, a poor design charger can waste substantial power needed to charge the battery. During the past decade, gallium nitride field effect transistors (GaN FETs) have been introduced that could replace power MOSFETs in conventional applications. The scope of this paper is to investigate if the implementation of GaN FET in the design of a charger can increase the charging efficiency of the charger.

Originally, the intention is to design a battery charger for an electric wheelchair and measure the efficiency. However, due to time constraint and complication in the implementation of GaN FETs, only the DC/DC converter will be designed. Figure 8 showed the general design of a battery charger. Because the GaN FETs and power MOSFETs are only being implemented in the DC/DC converter, any difference in efficiency will be determined in the converter stage.

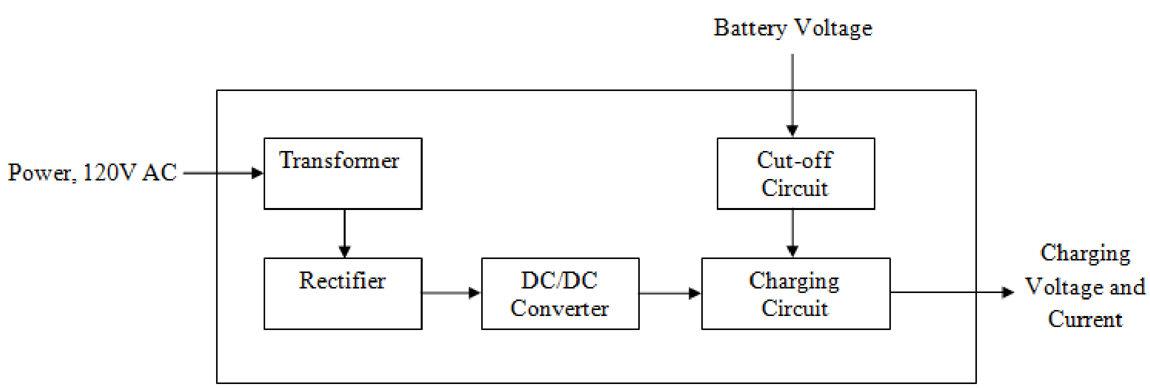

Figure 8. Block diagram of battery charger

3.1. DC-DC Converter Design Choice:

A battery charger is essentially a DC power supply. For step down application, a buck converter is the most used design and it can be either non-synchronous or synchronous. Non-synchronous topology is the simplest design for a buck converter. Figure 9 shows the modes of operation and waveforms for a non-synchronous buck converter. The advantage of this topology is in the simplicity of the circuit design and therefore, minimizes the system cost. The downside of this topology is power dissipation. In non-synchronous design, the power dissipation occurs in the switching device, the free-wheeling diode, and the driver transistor. Power losses on the free-wheeling diode effectively limit the maximum charge current to value significantly lower than those in synchronous designs [28].

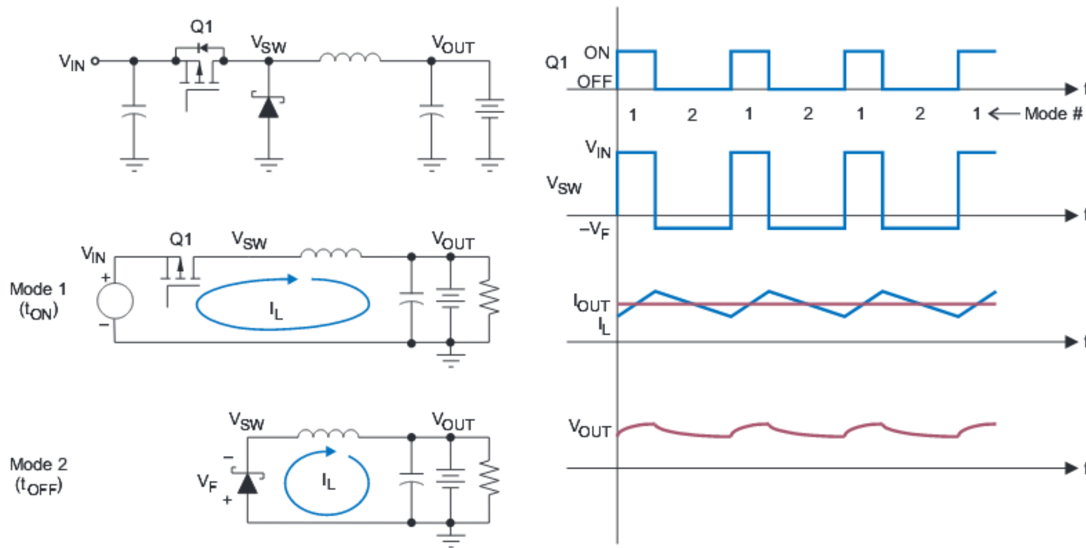

Figure 9. Modes of operation and waveforms for non-synchronous buck converter [28]

Synchronous topology is often chosen over non-synchronous in applications where the non-synchronous topology does not meet power dissipation and efficiency requirements. Figure 10 shows the modes of operation and waveforms for a synchronous buck converter. The difference between these two topologies is that another switching element is implemented in place of the diode for the synchronous design. Therefore, synchronous topology often costs more due to additional components and the complexity of the controller [28]. However, since the goal is to have maximum efficiency, the synchronous design is chosen. One thing that must be considered when designing a synchronous converter is the PWM signals driving the two FETs. For the synchronous design, the two FETs cannot be conducting at the same time or it will create a short circuit from power to ground and can destroy the converter. To prevent this from happening, there has to be sufficient dead time in between the on and off transition of the two FETs.

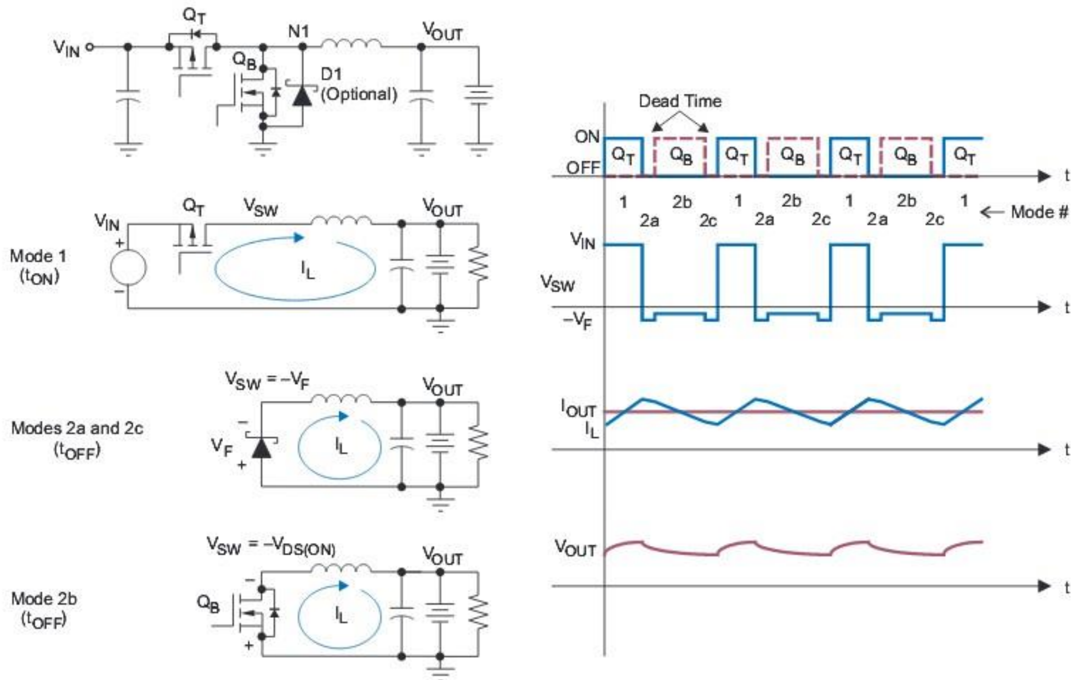

Figure 10. Modes of operation and waveforms for synchronous buck converter [28]

3.2. Components Design Choice:

The GaN FET chosen for the design was EPC2015. It has the voltage rating of 40V and can pass 33A continuously with only .004Ω of on resistance. To make a fair comparison, the Silicon power MOSFET has to have about the same specification as the EPC2015. For that reason, the SI4456DY was chosen for this application. One more thing to consider when selecting the ECP2015 is that the allowable gate voltage cannot surpass 6V or the IC will be destroyed. A gate driver is needed to make sure the gate voltage is below 6V. The LM5113 was designed for this purpose and therefore was selected for this application. To make sure that the efficiency result is unbiased, the same gate driver was used for the SI4456DY.

The next component is the PWM controller. As mention above, the synchronous converter needs sufficient dead time to make sure that the two FETs do not turn on at the same time. The TL494 was selected for the application. This IC is commonly used in switch mode power supply design. It has two outputs and is capable of operating over a wide range of frequencies (1 Hz to 300 kHz) along with a dead time control pin to adjust the dead time between pulses.

The last components to consider when designing a synchronous buck converter are the inductor and capacitor for the output stage. The minimum inductance is calculated based on the allowable ripple current and other specifications for the circuit. The basic equation for the inductor is

where is the ripple current in the inductor. The formula normally used to calculate the minimum inductance is

where

and LIR is the percentage allowable ripple current in the inductor. This value is normally 20% to 40% of the maximum current [29].

For the capacitor, the basic formula is

where is the ripple voltage of the capacitor. The minimum output capacitance due to the ripple voltage can be calculated using the equation below where CVR is the ripple voltage ratio. The equation above only takes into account the effect of the output ripple voltage and inductor ripple current on the output capacitance. The transient response on the load must also be considered. There is a temporary increase in the output voltage when the load current changes from a higher value to a lower value. This increase in voltage is called voltage overshoot, V_{OV}. The worst case overshoot will occur when the load transitions from maximum loads to no load. The output capacitor must be able to handle this transient condition [29]. The equation for minimum capacitance becomes

where

and

The minimum capacitance has to satisfy both equations mentioned above. The reader can refer to [29] for the full derivation for the inductor and capacitor formulas. The last thing to consider when selecting the inductor and capacitor is the parasitic series resistance also known as the equivalent series resistance (ESR). Minimizing ESR is key to obtaining a stable output voltage and current.

3.3. PCB Design:

Since the EPC2015 and SI4456DY are both surface mount devices, they could not be tested on a conventional breadboard. Instead, a custom printed circuit board (PCB) was designed for all testing. The design followed the guidelines for the EPC2015 because it was a relatively new device compared to the SI4456DY so there were a lot more constraints to consider. There were three layouts recommended by the manufacturer. They were single-sided termination, dual-sided termination, and filled-via dual sided termination. Due to cost, the single-sided termination layout was selected for the application. Figure 11 shows an example of a single-sided terminal layout configuration.

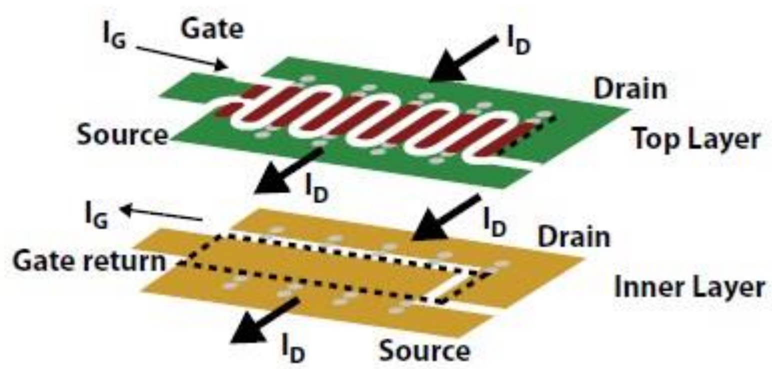

Figure 11. Single-sided terminal layout configuration [30]

The freeware version of Eagle was used to create the PCB layout for the testing. Because it was a free version, some of the recommendations could not be met. For example, the drain and source were supposed to be connected to additional layers using interlevel connections or vias to enhance the current carrying capability. The recommended via design was 10 mil (250 um) hole diameter and 20 mil (500 um) annular ring with two vias per pad for a total of 18 vias. However, the via design was too small for the standard board specification so only 6 vias were placed on the board. Another difference was the copper thickness. The standard board only allowed for 1 oz instead of the recommended 2 oz. The final design for both the EPC2015 and SI4456DY were shown in figures 20 and 21 in the appendix.

Chapter 4: Result and Analysis

Due to unforeseen problem with the gate driver, the synchronous buck converter was not completed. The results showed below were obtained from a non-synchronous buck converter design. A function generator was used to supply the pulse to the EPC2015 and SI4456DY. Since the only different between the synchronous and non-synchronous design is the implement of another FET instead of a diode, the calculations for all components remained the same. The design parameters were shown in table 4.

Table 4. Design parameters

Parameter	Value
Input Voltage	24 V
Output Voltage	15 V
Output Current	0.5 A
Frequency	100 kHz
Duty Cycle	62.5%
Inductor	375 uH
Capacitor	2.62 uF
Output Load	30 Ω

Since the objective is to compare the efficiency, the input and output voltage and current were measured for both converters. Table 5 shows the results from the first test run.

Table 5. Results from first test

	EPC2015	SI4456DY
Input Voltage	23.5 V	23.5 V
Input Current	0.07 A	0.03 A
Output Voltage	3.34 V	1.66 V
Output Current	0.11 A	0.05 A
Efficiency	22%	12%

As far as efficiency was concerned, test results indicate that the EPC2015 showed better efficiency than the SI4456DY. However, this was only when the gate voltage was running at 5V. For the EPC2015, a gate voltage of 5V allowed the FET to perform at its best. For the SI4456DY, a 10V gate voltage was required. Therefore, a second test was run with EPC2015 at 5V gate and SI4456DY at 10V gate and the efficiency was then compared again. Table 6 shows the results from the second test.

Table 6. Results from second test

	EPC2015	SI4456DY
Input Voltage	23.5 V	23.5 V
Input Current	0.07 A	0.08 A
Output Voltage	3.34 V	4.4 V
Output Current	0.11 A	0.14 A
Efficiency	22%	33%

As observed from table 6, the MOSFET now showed better efficiency than the eGaN FET. This was attributed to several possible causes. First, the pulse on the gate of the GaN FET had excessive ringing when compared to the pulse applied to the MOSFET,as shown in figures 12 and 13. This was attributed to a mismatch in impedance between the interconnect and the gate of the FET. Ringing was undesirable because it reduces the efficiency of the circuit and endangers the FET. Because there was more ringing on the GaN FET, it could not be driven to its limits and its efficiency was lower. Secondly, the GaN FET was designed to be operated at higher frequencies (500 kHz to 1 MHZ) than our equipment could safely produce. The 100 kHz frequency may have worked better for the MOSFET instead. However, the ringing became worse at higher frequency. The ringing of the GaN FET pulse has to be fixed before increasing the frequency otherwise it would damage the device and reduce the performance even further.

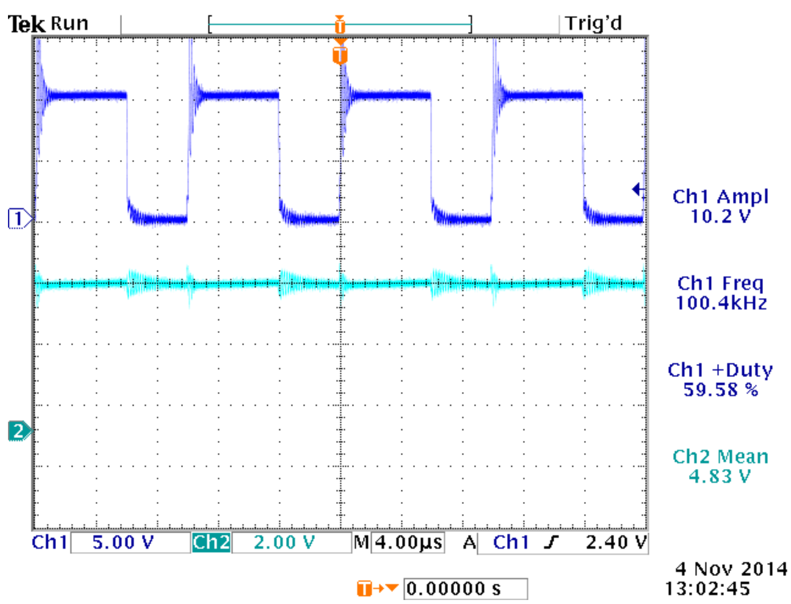

Figure 12. Ringing on MOSFET pulse

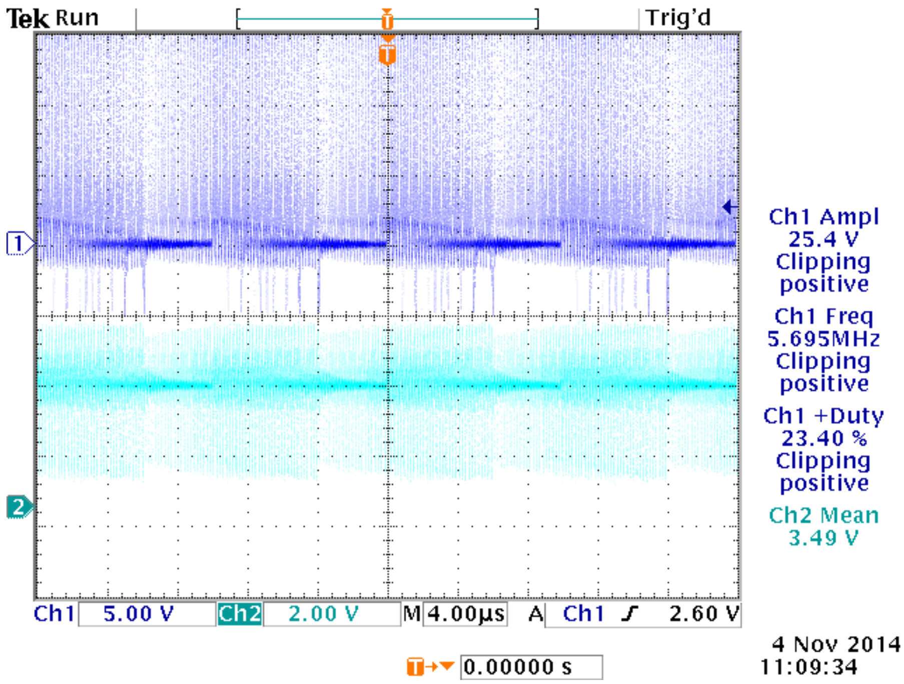

Figure 13. Ringing on eGaN FET pulse

An attempt was made to reduce the ringing by inserting a small value capacitor (in nF range) between the gate and ground of the FET. However, this only reduced ringing in the MOSFET and not the GaN FET. At this point, it would have been best to go revise the PCB design. It would seem that the current board design was not suited to operate the EPC2015. Another problem was that the efficiency was below expectation for both converters. Non-synchronous converters should be at least 70% efficient. It seemed that most of the power was lost somewhere within the circuit. There were three places to check for power loss: the inductor, the diode, and the transistor. After checking, the inductor and the diode exhibited no signal loss. Therefore, most of the power loss was caused within the transistor. Figure 14 shows the signal of the gate and source of the MOSFET.

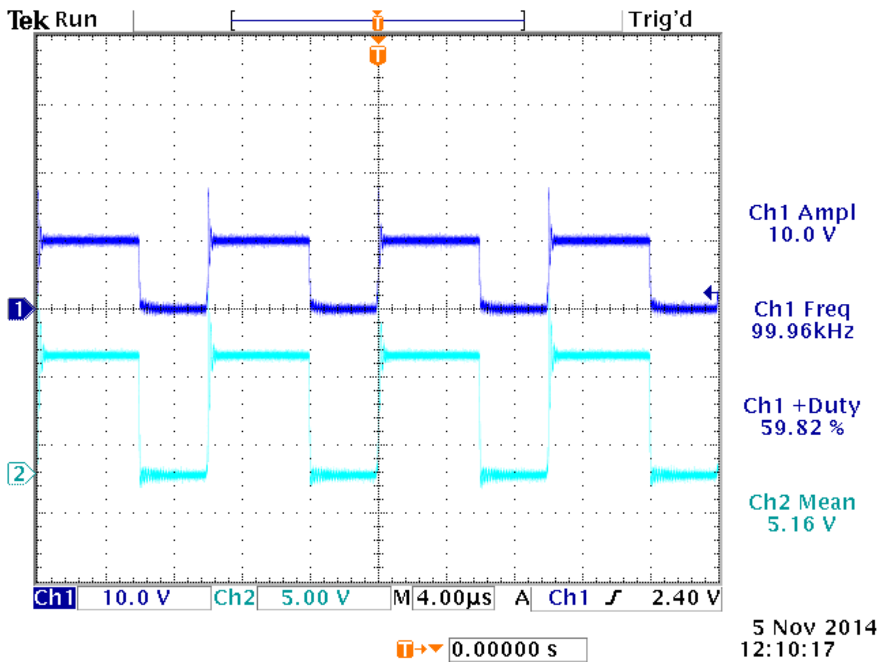

Figure 14. Gate and source signal of MOSFET

Because the supply voltage was 24V, the pulse on the source should be close to 24V. However, as observed on the scope, the pulse on channel 2 only had about 10V amplitude. This would explain why the output voltage was lower than expected. In theory, the output voltage only depends on the duty cycle. However, the gate voltage must also be taken into account when design the non-synchronous buck converter. From figure 14, the source voltage can only get as high as the gate voltage. Therefore, for the source to get to 24V, the gate has to be 24V. However, the FETs chosen for this experiment were not designed for 24V gate voltage and in turn did not perform at their best potential using the original parameters. Therefore, to achieve a better efficiency as well as have a better comparison between the GaN FET and MOSFET, the design parameter was changed. Table 7 shows the new parameters.

Table 7. New Design Parameters

Parameter	Value
Input Voltage	4 V
Output Voltage	2 V
Output Current	0.2 A
Frequency	100 kHz
Duty Cycle	50%
Inductor	200 uH
Capacitor	27 uF
Output Load	10 Ω

Table 8. Results from third test

	EPC2015	SI4456DY
Input Voltage	4.26 V	4.26 V
Input Current	0.08 A	0.1 A
Output Voltage	1.75 V	1.99 V
Output Current	0.15 A	0.18 A
Efficiency	77%	84.1%

Table 8 shows the results from the third test run. The efficiency was considerably higher than before because the FETs were able to perform at their full potential. Figure 15 shows that the source voltage was comparable to the input voltage during the on time.

The pulse of the GaN FET also did not have as much ringing as before. Figure 16 shows the pulse on the gate of the EPC2015. Because the pulse was clean, it seems that in addition to impedance mismatch, the ringing in figure 13 was also caused by the large voltage drop between the drain and the source of the GaN FET. The efficiency of the GaN FET was still lower than the MOSFET. This was because the high level of the source signal of the eGaN FET was lower than that of the MOSFET.

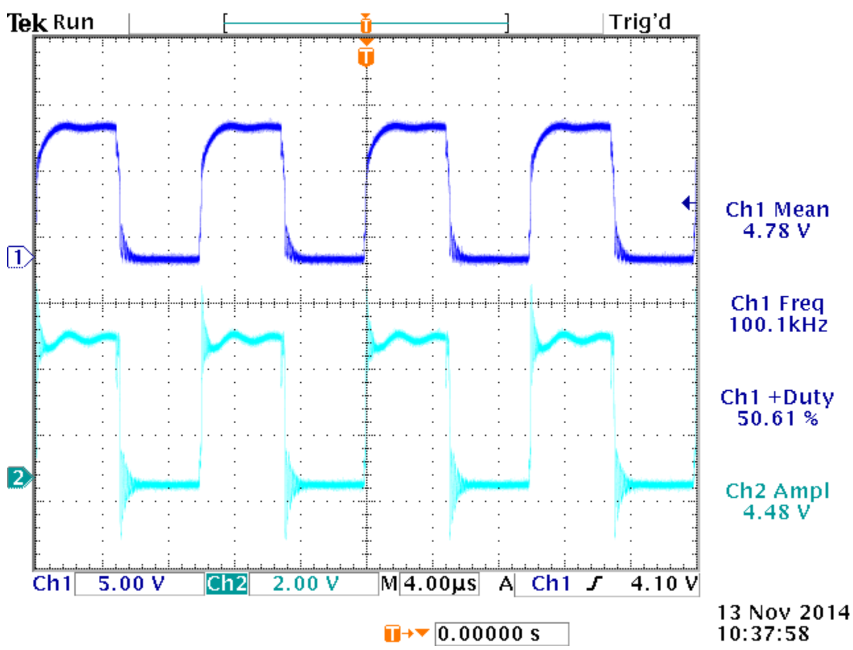

Figure 15. Gate and source voltage of MOSFET

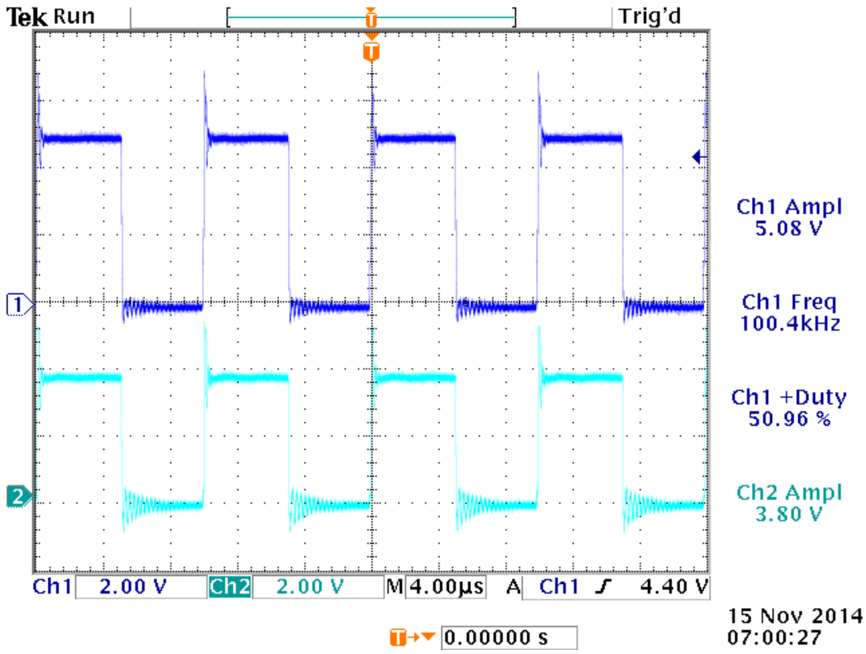

Figure 16. Gate and source voltage of eGaN FET

The fourth test was performed by increasing the gate voltage of the eGaN FET to its maximum limit of 6V to see if the efficiency is improved. Table 9 shows the results from the fourth test run.

Table 9. Results from fourth test run

	EPC2015	SI4456DY
Input Voltage	4.28 V	4.26 V
Input Current	0.1 A	0.1 A
Output Voltage	1.98 V	1.99 V
Output Current	0.18 A	0.18 A
Efficiency	83.3%	84.1%

The result showed that by running the gate of the eGaN FET at 6V, the efficiency was improved to about the same as that of the MOSFET.

Chapter 5: Conclusion

From the result of the experiment, the GaN FET was not able to improve the efficiency of the DC-DC down converter. The efficiency was about the same at best. It would appear that the non-synchronous buck converter design was not sufficient enough to accurately compare the efficiency between the two switching devices. The original goal was to test the two devices using synchronous design. However, that was not possible due to unforeseen problems associated with the gate driver.

Even though the result did not show any improvement in efficiency, it should be noticed that the GaN FET was able to achieve the same efficiency as the MOSFET by applying only 6V to the gate instead of 10V. This makes GaN FET more efficient when there is a low gate voltage limit in the design.

Because the parameters were modified to obtain reliable test results for comparison, future works would include figuring out the problem with the gate driver so that the original parameters can be tested using the synchronous design to accurately access the performance of the GaN FET. Another area to explore is the frequency of the converter. The GaN FET was designed to work at high frequency (MHz range). However, because the PCB design did not meet the specifications required by the manufacturer, the frequency was set low to minimize the effect of parasitic inductance on the performance of the GaN FET. It would be beneficial to increase the switching frequency in future to have the GaN FET perform at its best condition.

The operating temperature should also be investigated. Since GaN FET has positive temperature coefficient which raises the on-resistance of the device as temperature increases, the FET may dissipate more power during switching cycle which effectively lower the efficiency. However, the temperature coefficient of GaN FET is lower when compared to MOSFET. Therefore, GaN FET should have lower efficiency loss when operate at high temperature. Other research could include improving the design of the PCB to meet all the specifications required for implementing of eGaN FET. Because eGaN FET is still new compare to Si MOSFET, a poorly designed PCB could affect the eGaN FET more than the MOSFET.

Appendix

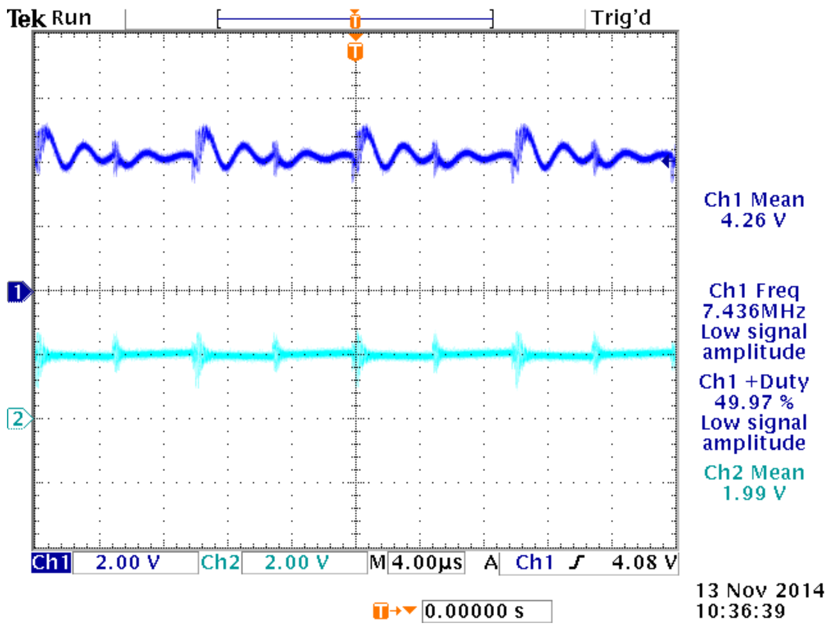

Figure 17. Input and output voltage of MOSFET

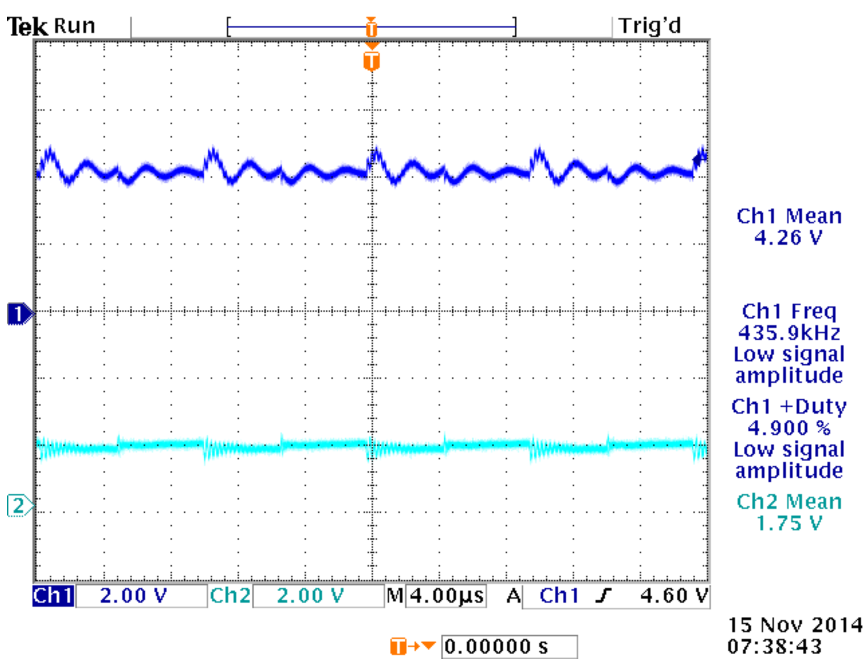

Figure 18. Input and output voltage of eGaN FET (running at 5V gate)

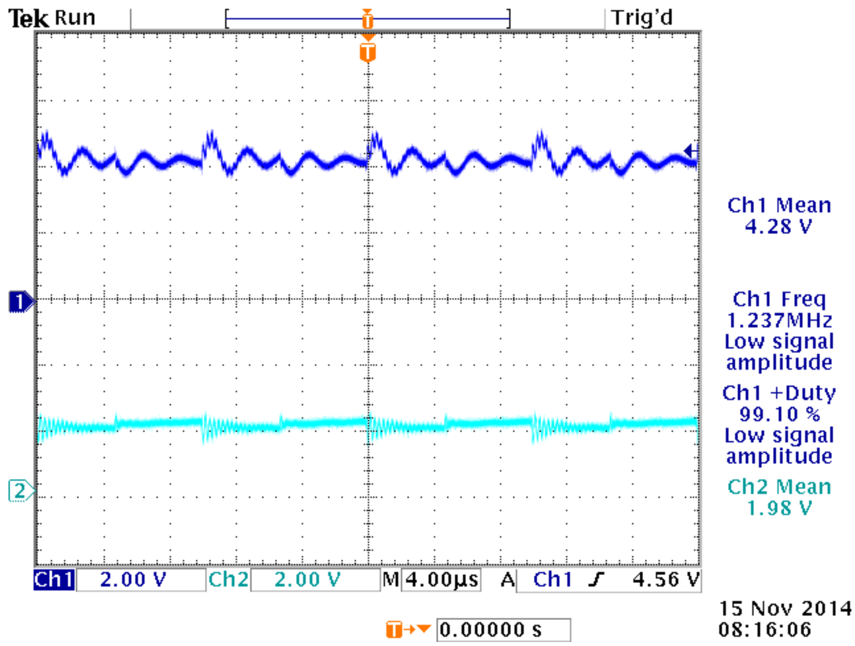

Figure 19. Input and output of eGaN FET (Running at 6V gate)

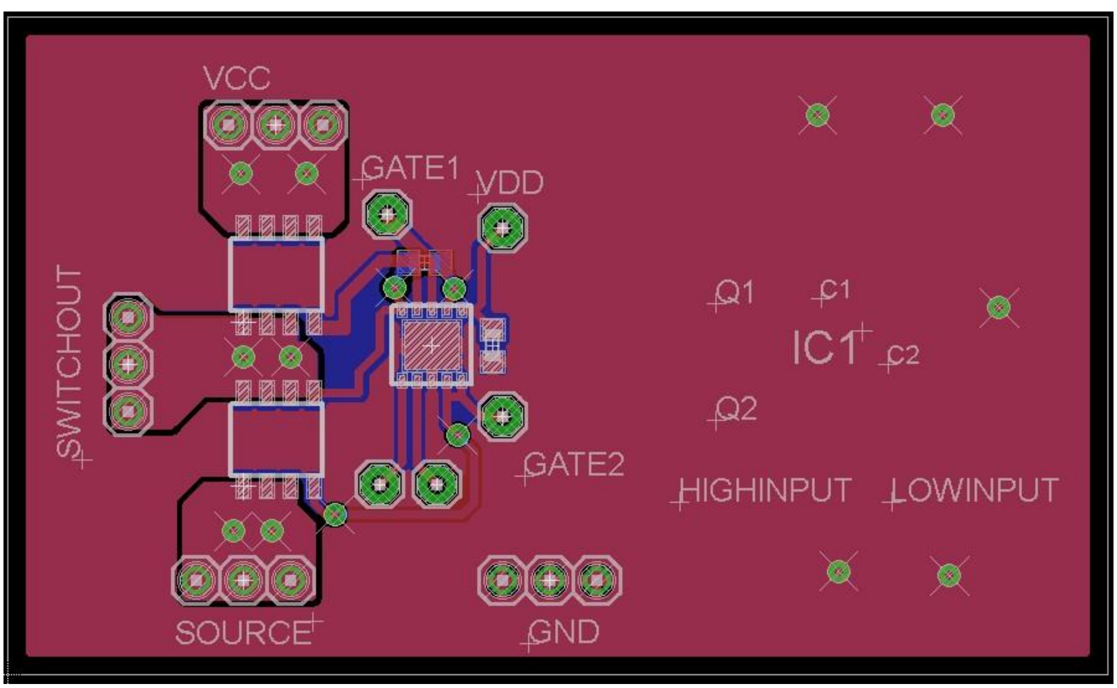

Figure 20. PCB design for MOSFET

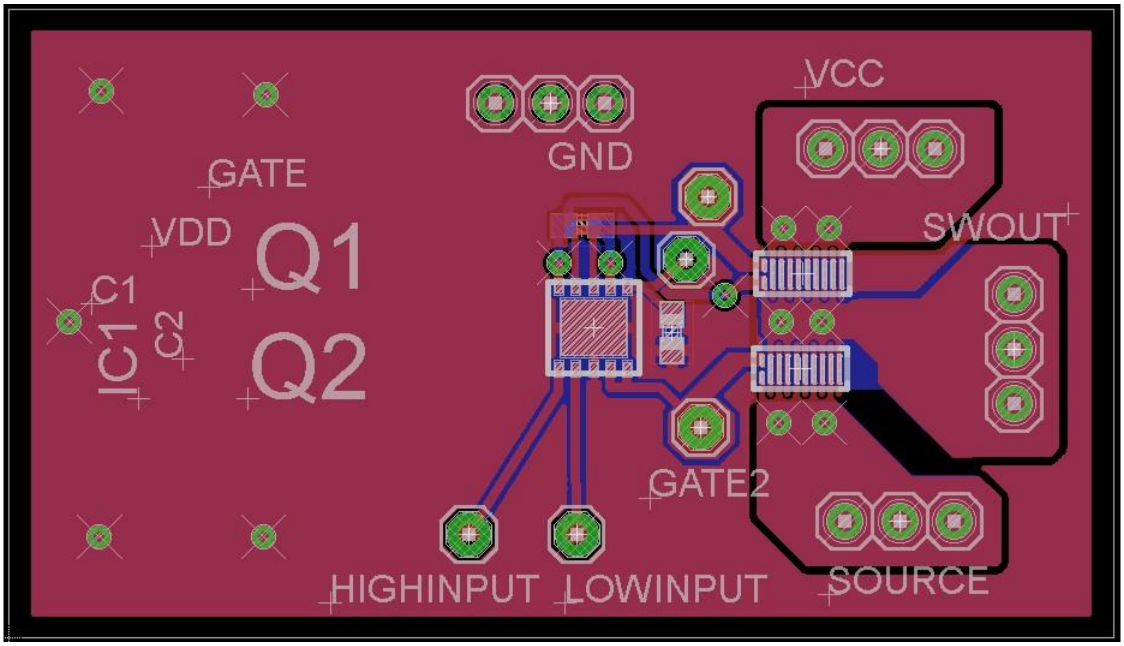

Figure 21. PCB design for eGaN FET

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- Assisted in creating a validated method used to assess the reliability of the gate driver board for power electronics systems
- Conducted literature review and performed research on methods used to assess the reliability of power electronic systems
- Performed infrared thermography of power electronics system to calibrate Physics-of-Failure simulation model
- Prepared culminating report, developed poster presentation and relayed all research efforts to peers and supervisors

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Supervisor: Mr. Lester Llanman

- Documented maintenance tasks for all new equipment in the plant
- Learned the operation of the management software and created maintenance schedule for all equipment
- Created manual on how to use the management software for future reference

Awards:

Dean's List

Phi Kappa Phi

Activities/Presentations:

Institute of Electrical and Electronics Engineers (IEEE), Student Branch, Penn State Harrisburg, 2011 – Present