White Paper

# Wide Bandgap Semiconductors are Revolutionizing Battery Charger Design and Performance

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## Abstract

The latest generation of wideband gap semiconductors, both Silicon Carbide (SiC) and Gallium Nitride (GaN), have reached a point of reliability, availability, and cost effectiveness to enable wide scale adoption into high frequency switched-mode battery charger and inverter applications at all power levels. With their adoption, further reductions in physical size, weight, and cost per watt will be obtained compared to both high frequency traditional MOSFET based switched-mode power conversion topologies and traditional line frequency (50 or 60 Hz) power conversion topologies. Additionally, the technology allows for higher efficiency designs which can operate at higher voltages with faster dynamic response and lower output ripple. This translates into more power in less space, which is more reliable, easier to install and service, and less costly to operate.

## Size, Weight, Ease of Service and Efficiency DO Matter – Provided We Don't Sacrifice Reliability and Uptime

Industrial and utility battery chargers and UPS are some of the last adopters of high frequency power conversion. High reliability and low failure rates matter more than anything to readers of this paper.

The only difference between hardening high frequency and line frequency (e.g. SCR) power converters to survive difficult environments is just the size of engineering task. It's more difficult to harden high frequency technology than SCR or IGBT. Properly engineered high frequency power converters have been employed for decades with great success in the most demanding aerospace and military power systems. These applications' requirements are more challenging than the requirements of power utilities or industry.

Wide bandgap semiconductors make the engineer's job of creating robust power converters easier, and enable reductions in the size, weight, and cost compared to silicon MOSFET-equipped high frequency designs. Properly applied, wide bandgap semiconductors enable us to figuratively have our cake and eat it.

This paper summarizes what wide bandgap semiconductors are, how they differ from silicon MOSFET technology, and illustrates advantages over silicon MOSFET technology in efficiency, volume, and weight.

Finally, we compare our own field failure rate experience of traditional SCR designs versus wide bandgap semiconductor-equipped switch-mode battery chargers in the identical application.

## Wide Bandgap Semiconductor Background

The name wide bandgap semiconductor originates from the higher atomic band gap of the materials used to make them versus conventional semiconductors and is associated with smaller atoms with strong atomic bonds. Band gap is measured in electron-volts (eV) and represents the amount of energy required for an electron to move from one energy band to another. Specifically, it is the energy difference between the highest occupied state in the valence band and the lowest unoccupied state in the conduction band of a solid material where the valence band represents the range of electron energies in which electrons are normally present and the conduction band represents the range of electron energies in which electrons are normally empty.

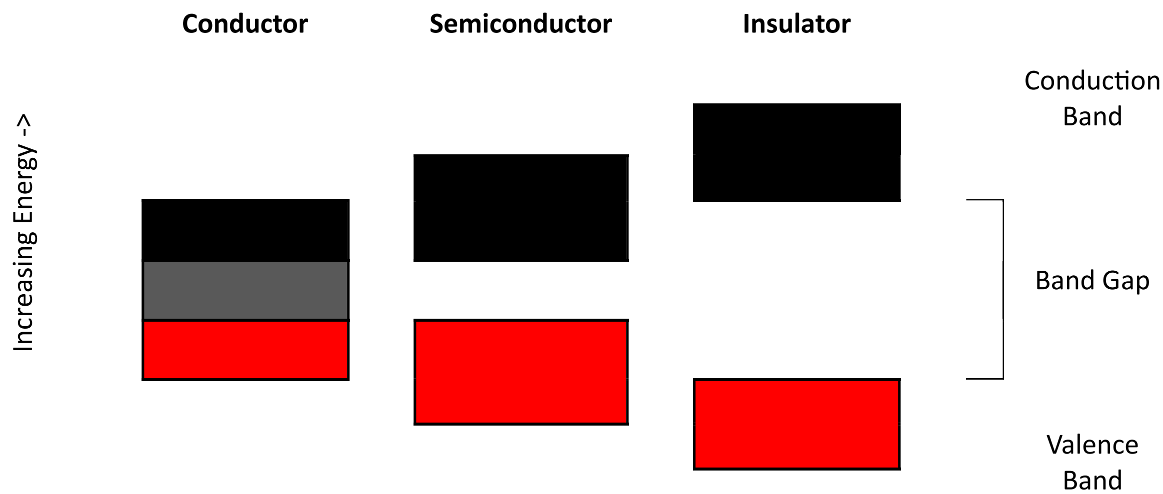



Figure 1 – Band Gap

If a material's bandgap energy is high, ranging from approximately 3 eV to 7 eV, the material is considered an insulator. In an insulator, it takes a very large amount of energy to move an electron between the energy bands to create current flow. In conductors at room temperature, there is overlap between the conduction and valence bands where electrons can flow easily and current flows readily. In semiconductors, the bandgap energy is relatively low, typically 3 eV or less. As a result, it takes a relatively small amount of applied energy in a semiconductor to move electrons between the valence band and conduction band to create electrical current flow. The ability to create controlled current flow with small amounts of applied energy is what makes semiconductors useful in electronics. See figure 1 above.

Conventional silicon semiconductors found in silicon MOSFETs, IGBTs, and switching diodes have a band gap of approximately 1.1 eV. In contrast, the most commercially prevalent wide band gap semiconductors, Silicon Carbide (SiC) and Gallium Nitride (GaN) have band gaps of approximately 3.2 eV and 3.4 eV respectively, and are considered weak insulators. See the table below for a summary of Si vs SiC vs GaN material properties. The wide bandgap semiconductor's greater band gap energy results both directly and indirectly in many beneficial properties versus conventional silicon semiconductors in electrical switching applications. Note that the wide bandgap semiconductors also have advantages in light-emitting diodes (LEDs) and semiconductor lasers which is outside the scope of this paper.

| **Material Property** | **Si** | **SiC (4H)** | **GaN** |
|---|---|---|---|
| Bandgap (eV) | 1.1 | 3.2 | 3.4 |
| Electric breakdown field (kV/cm) | 300 | 3500 | 4900 |
| Electron mobility ($cm^2/V \cdot s$) | 1500 | 1000 | 2200 |
| Saturated electron drift velocity ($10^6$ cm/s) | 10 | 22 | 25 |
| Melting Point ($^oC$) | 1400 | 2700 | 2500 |
| Thermal conductivity (W/cm·K) | 1.5 | 4.9 | 1.3 |

Table 1 – Material Properties of Silicon (Si), Silicon Carbide (SiC) and Gallium Nitride (GaN) Semiconductors

### Higher Junction Temperature Operation

As the junction operating temperature of a semiconductor increases, the energy of the electrons in the valence band also increases. Eventually, when the temperature gets hot enough, electrons have sufficient energy to jump to the conduction band and uncontrolled conduction of the semiconductor occurs. Since wide bandgap semiconductors require more energy for an electron to move from the valence band to the conduction band versus conventional silicon semiconductors, this occurs at a higher operating temperature. For traditional silicon semiconductors, the maximum junction temperature is around 150 °C. For Silicon Carbide (SiC) and Gallium Nitride (GaN) the maximum junction temperature can be 600 °C or higher. It is important to note that although the operating temperature is higher for wide bandgap semiconductors, the packaging of the dies into traditional plastic-based electronic component packages limits the operating temperatures to much lower values (175 °C to 200 °C).

### Higher Breakdown Voltage and Breakdown Field with Lower Leakage Currents

The breakdown voltage of an insulator is the minimum voltage at which the material fails as an insulator, becomes conductive, and allows uncontrolled current flow. This is often referred to as the avalanche breakdown voltage in a semiconductor material. Inherent to wide bandgap semiconductors are higher breakdown voltages and higher breakdown fields where the breakdown field is a measure of the dielectric strength of a material after the material receives enough energy to jump the band gap. The high electrical breakdown properties are due to the higher bandgap energy required to promote an electron from the valence band to the conduction band and their smaller atomic crystal structure and tighter bonds versus conventional silicon semiconductors. Having a higher breakdown voltage allows electrical device designs that can operate at higher voltages with lower leakage currents versus traditional silicon semiconductors. While operation at higher voltage is beneficial by itself, it also allows for further enhancements to the devices.

### Lower On-Resistance for High Voltage Rated Parts

Higher electrical breakdown field allows for higher semiconductor doping. Doping is the process of introducing impurities into a semiconductor material to change its electrical conductivity. The process of doping can be used to increase the number of free electrons and conductivity of the material. The net result is lower on-resistance in high voltage rated parts versus conventional silicon semiconductors allowing for much lower conduction losses and gains in efficiency in higher voltage applications.

### Reduced Losses through Thinner Device Layers

Another benefit of the higher electric breakdown field and the higher doping density is that wide bandgap semiconductor device layers can be made thinner than conventional silicon semiconductors with the same breakdown voltage. Thinner layers result in lower storage of minority carriers in a device which reduces the reverse recovery losses (Qrr). Lower reverse recovery losses allow for higher frequency operation and improved efficiency. Furthermore, smaller die size significantly reduces the required gate-drive power requirements versus conventional silicon devices. This further improves overall system losses and efficiency.

## Higher Frequency Operation

Electron mobility is a measure of how quickly an electron (i.e. current) can accelerate under an electric field in a semiconductor and is a measure of conductivity. Saturation velocity is a measure of the maximum attainable speed of an electron in a semiconductor under a high electric field. Higher saturation velocity allows stored charge in the depletion region of a device to be removed more quickly and reduces the reverse recovery current. Having both high electron mobility and high saturation velocity offers faster and easier electron transport resulting in higher frequency operation. Silicon Carbide (SiC) and Gallium Nitride (GaN) offer more than twice the saturation velocity of convention Silicon (Si), and GaN has higher electron mobility than both Si and SiC offering the highest switching speed of all three.

## Higher Thermal Conductivity

While not directly related to its band gap, Silicon Carbide also has a thermal conductivity advantage over both Silicon and Gallium Nitride. In fact, GaN and Si have similar thermal conductivity of around 1.3 to 1.5 W/cm·K respectively while SiC has a thermal conductivity around four times higher at approximately 4.9 W/cm·K. This means that heat generated in a SiC device will conduct to its surrounding case and heatsink more quickly, and device temperatures will increase more slowly. Ultimately, SiC devices have operation advantages at higher power levels versus GaN and Si devices.

## Falling Part Cost

The table below compares the current cost of three similar Silicon (Si), Silicon Carbide (SiC), and Gallium Nitride (GaN) MOSFETs with identical voltage ratings (Vds) and similar on-resistance (Rds Ω). Despite the similar ratings, the SiC part cost 2.2 times the convention Si part. The GaN part costs 2.8 times more than the Si part and 1.3 times more than the SiC part.

| **Material** | **$V_{ds}$ (25°C)** | **$R_{ds}$ Ω (25°C)** | **$R_{ds}$ Ω (100°C)** | **$Q_{gtot}$ (nC)** | **$Q_{rr}$ (nC)** | **$C_{oss}$ (En Rel pF)** | **RθJC (°C/W)** | **1k Cost ($)** |
|---|---|---|---|---|---|---|---|---|
| Silicon | 650 | 0.11 | 0.19 | 41.0 | 560 | 1626 | 1.1 | 2.46 |
| SiC | 650 | 0.16 | 0.18 | 28.0 | 89 | 114 | 1.53 | 5.35 |
| GaN | 650 | 0.10 | 0.20 | 5.2 | 0 | 157 | 2.2 | 6.87 |

Table 2 – Comparative MOSFET Characteristics

Historically, much of this cost difference has been attributed to a less mature manufacturing process for GaN and SiC parts where the wide bandgap parts may have thousands of crystal defects per square centimeter versus less than 100 for silicon wafers. However, substantial improvements have been made in material quality for both SiC and GaN over the last several years to where defects are no longer the driving issue. As it stands today, the SiC production process is more developed than GaN, producing larger substrate sizes and more parts per wafer, but the base materials and energy required to produce a SiC part are much higher than that for a silicon part. Cost reductions in SiC parts are primarily coming with the introduction of each new generation of parts where the die sizes are reduced resulting in parts with lower on-resistance (higher performance) and more parts per wafer (lower cost). In contrast, GaN devices are grown on standard and readily available silicon substrates and some low voltage GaN parts are even on par with the current silicon manufacturing cost, but volumes are not, which keeps GaN prices higher for now. As volumes continue to increase, prices are expected to continue to fall. Higher device costs are also offset by the system level cost reductions through higher efficiency and higher operating frequency driving smaller capacitors, inductors, heatsinks, and physical enclosure sizes.

## Tested Reliability

The reliability of silicon parts is often no longer questioned. They have been used in millions of applications, including automotive, aerospace, and military, for more than 25 years. However, the reliability of SiC and GaN parts is less established as they are newer, less widely adopted, and manufacturing defects have slowed their development. To establish SiC and GaN reliability, manufacturers and designers have looked at the inherent defects in the part structures, reliability testing, industry adaptation, and applied stresses in the end application.

For SiC parts, the gate oxide reliability is the main concern. SiC substrate defects or process variations may cause local oxide thinning that can result in early breakdown and device failure when exposed to high electric fields. To counter this, the gate oxide formation process is monitored and controlled carefully, and device screening steps are implemented, including burn-in test, to detect early failures. For GaN parts, the main concern is that trapped electrons within the device layers will cause irreversible increases in the on-resistance of the part over time. However, this issue can be controlled within the manufacturing process through process controls during the creation of the dielectric layers and their interfaces.

Furthermore, for parts to be adopted widely in mass markets such as the automotive industry, they must have failure rates demonstrated in the parts per billion (ppb) range like silicon parts. To demonstrate such reliability, highly accelerated life testing has been done to the JEDEC (Joint Electron Device Engineering Council) JC-70 standard for testing and evaluating wide bandgap devices, and many parts have been qualified to AEC (Automotive Electronics Council)-Q101 which defines stress test driven requirements and conditions for discrete electronic components in the automotive world. With testing complete, SiC and GaN parts are now being widely adopted into the automotive industry for use in traction control motors and electric vehicle charging.

Part reliability is also a function of applied stresses in the end application. The wear-out accelerators, such as temperature and voltage are the same for SiC and GaN as they are Si. Parts must be used within their ratings and deratings must be applied. Higher voltage ratings, higher thermal conductivity, and lower losses for wide bandgap parts versus silicon parts allow for higher part deratings when using SiC or GaN in place of a Si part with the same stresses applied, resulting in higher overall reliability.

## 100 kHz Operating Comparison

The typical buck converter, as shown in the figure below, can be used to show the relative performance, cost, and size differences of a converter using Silicon (Si), Silicon Carbide (SiC) and Gallium Nitride (GaN) semiconductors. The buck converter is a commonly used topology to create a regulated output voltage lower than the input voltage in battery chargers and power supplies. In the topology, the upper switch (Q1) is hard switched. Hard switched means that the switch is turned off or on with simultaneous current flowing through it and voltage across it. Hard switching topologies best demonstrate the advantages of wide bandgap semiconductors because the switching losses of wide bandgap semiconductors are lower. To make the comparison as informative as possible Si, SiC, and GaN MOSFETs with identical voltage ratings and similar on-resistance were selected for Q1 and Q2. See table 2 above for the selected device parameters. Note that Q1 and Q2 are identical parts in this example.

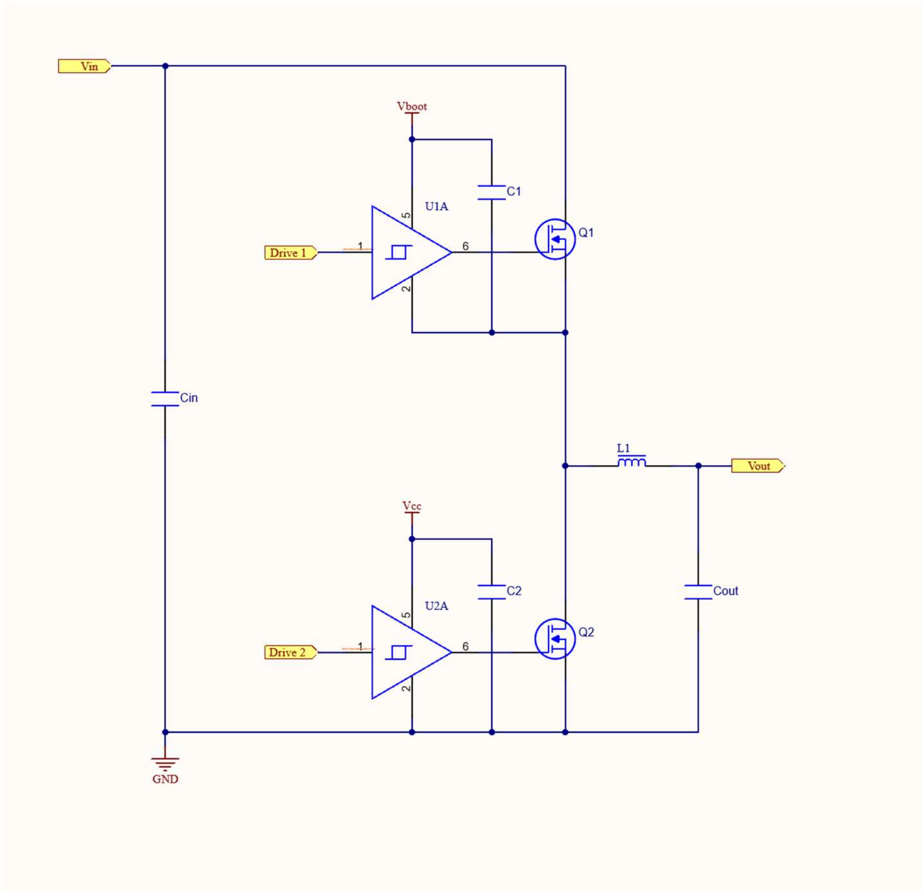


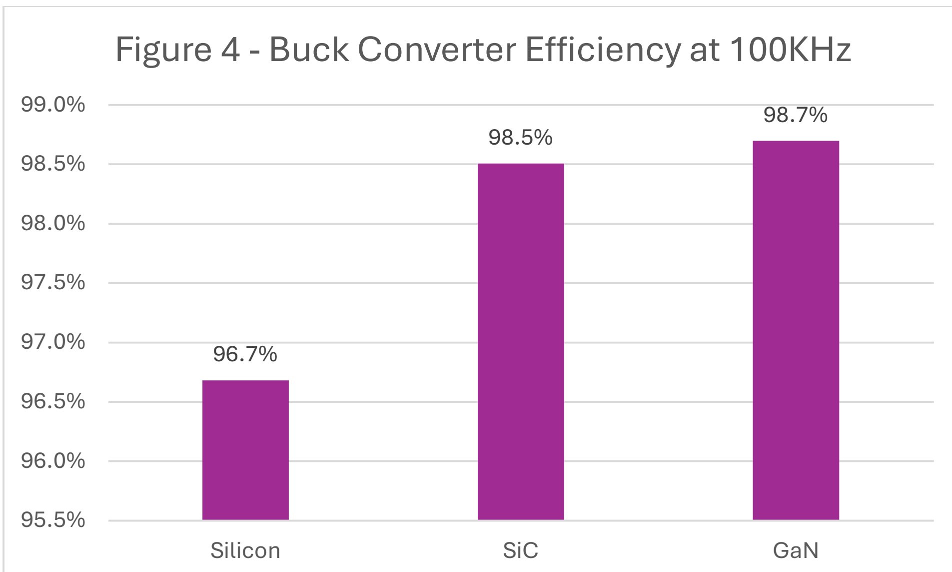

Figure 2 – Buck Converter

Currently, there is a lot of competition in the semiconductor market around 650 V rated parts. 650 V parts are used in a lot of applications including a typical 100V-264 Vac input converter seen on many chargers and inverters. Applications requiring parts rated higher than 650V generally use SiC parts because GaN parts are not readily available at ratings over 650 V. In contrast, SiC parts are widely available in 1,000 V, 1,200 V, 1,800 V, and even 3,000 V. At these higher voltage levels, SiC parts offer lower gate capacitance, lower on resistance, and faster switching speed than the IGBTs historically used in these applications. Below 650 V, GaN parts offer lower on resistance, simpler gate drives, and even higher switching speeds than SiC parts. In the 650 V range and below conventional Silicon MOSFETs are also common as well where cost is prioritized over smaller size, and in topologies utilizing soft switching techniques where switching loss is lower. To compare parts in the competitive 650 V range, the following design parameters were selected for the buck converter design.

| | |
|---|---|
| **Input Voltage** | 400 Vdc |
| **Output Voltage** | 200 Vdc |
| **Output Current** | 5 A |
| **Output Voltage Ripple** | 0.3 Vrms or less |

Table 3 – Buck Converter Design Parameters

As a baseline comparison, a complete buck converter design was completed for all three semiconductor technologies at 100 kHz. All three designs used identical output inductors, input capacitors, and output capacitors. And no consideration was given to the maximum amount of heat that a part could dissipate. Using these limitations, the graph below shows the total efficiency of each design.




As can be seen in the graph above, the wide band gap semiconductor designs had the highest overall efficiency, with GaN having the best efficiency of 98.7%. Since the designs use the same switching frequency with identical output inductors, and all the semiconductor switches were selected to have very similar on-resistance, the primary difference in efficiency between the converters is the switching loss in Q1. The graph below shows the component losses for each design. Note that the switching losses for Q2 are ignored as the switch is turned off before its voltage begins to rise and is turned on only after its voltage reaches zero.

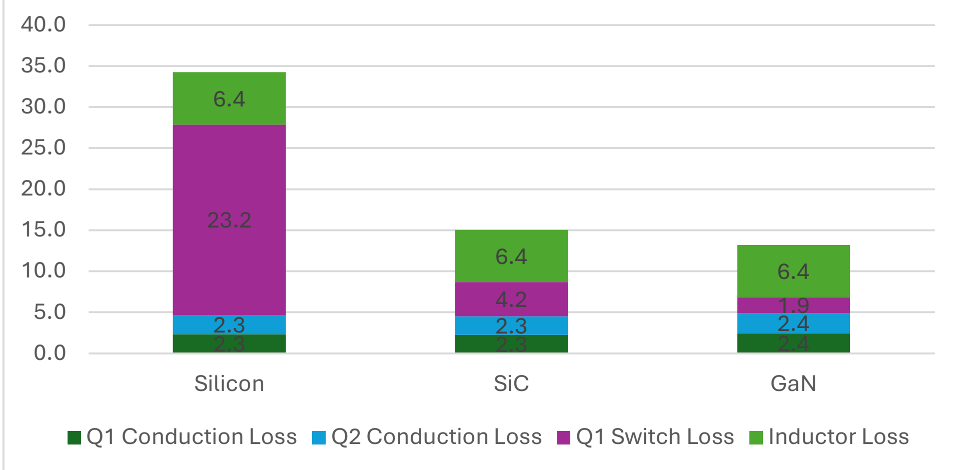
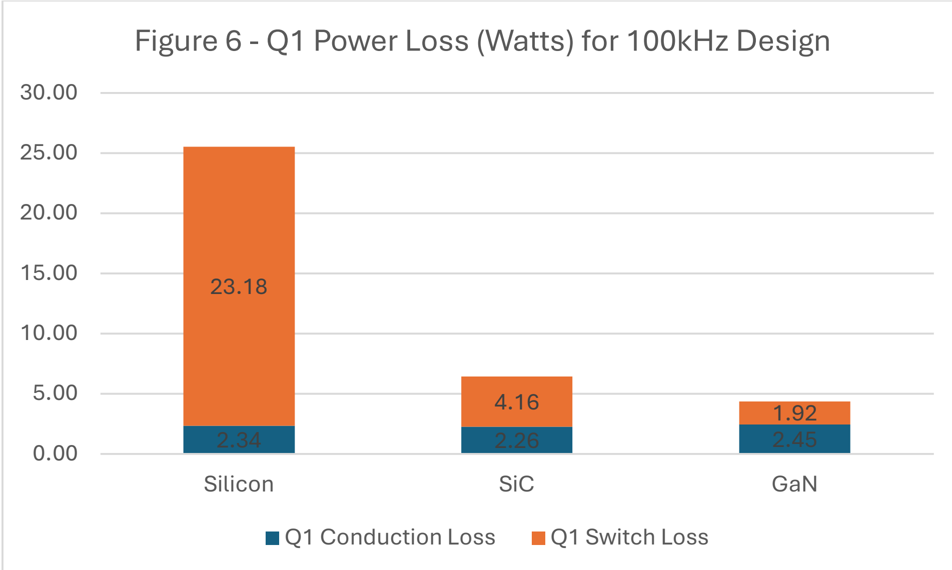



Figure 5 - Total Component Power Losses at 100KHz (Watts)

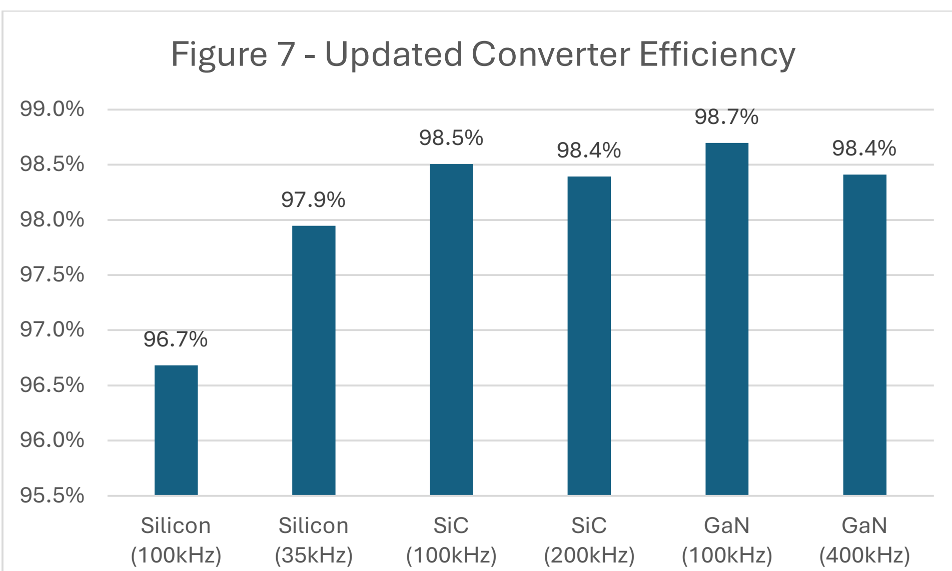
While an overall efficiency of 96.7% may be acceptable in the end application, looking closer at the component loss distribution reveals a power dissipation problem in the Q1 Silicon design. Q1 power losses are shown in the figure below. The total power loss in Q1 is the sum of the conduction loss, which is a function of the output current squared multiplied by the component's on-resistance, plus the switching losses. The switching losses are directly proportional to the switching frequency and include Eoss (representing the stored capacitance between the source and drain), turn-on cross-conduction loss (representing the turn on time of the MOSFET), and Qrr (representing the reverse recovery charge during turn-on and the energy required to charge the non-linear Coss of Q2)

In the Si design the total power loss in Q1 is greater than 25 watts, which is unacceptably high. For a typical discrete MOSFET packaged in a TO-247 or similar package, power dissipation should be held to around 10.5 watts or less to keep the junction temperature of the part below its rating. For the SiC and GaN designs, the power dissipation in Q1 is only around 5 watts or less which means that we can look at increasing the switching frequency to reduce the overall size of the converter without power dissipation problems in the switch.

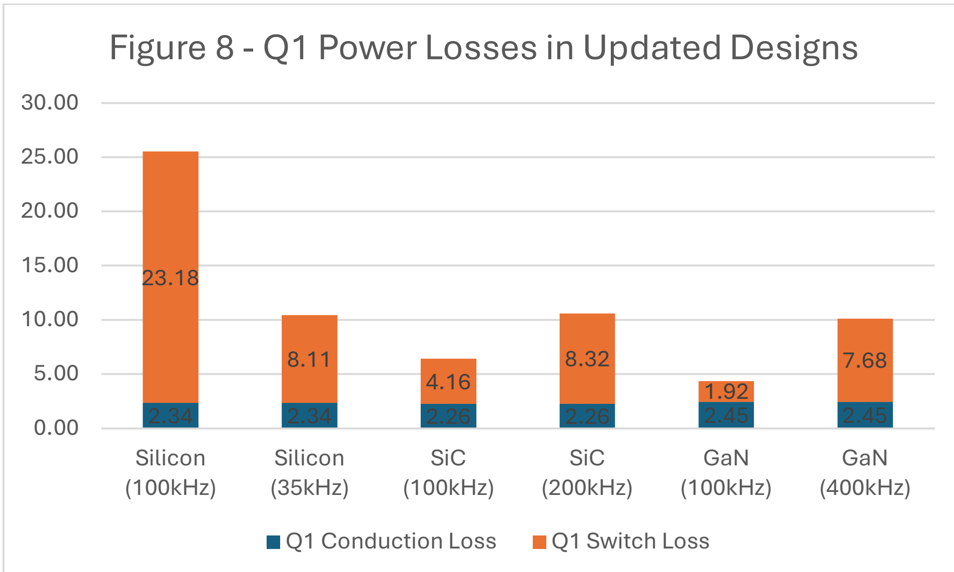



## Optimum Operating Frequency Comparison

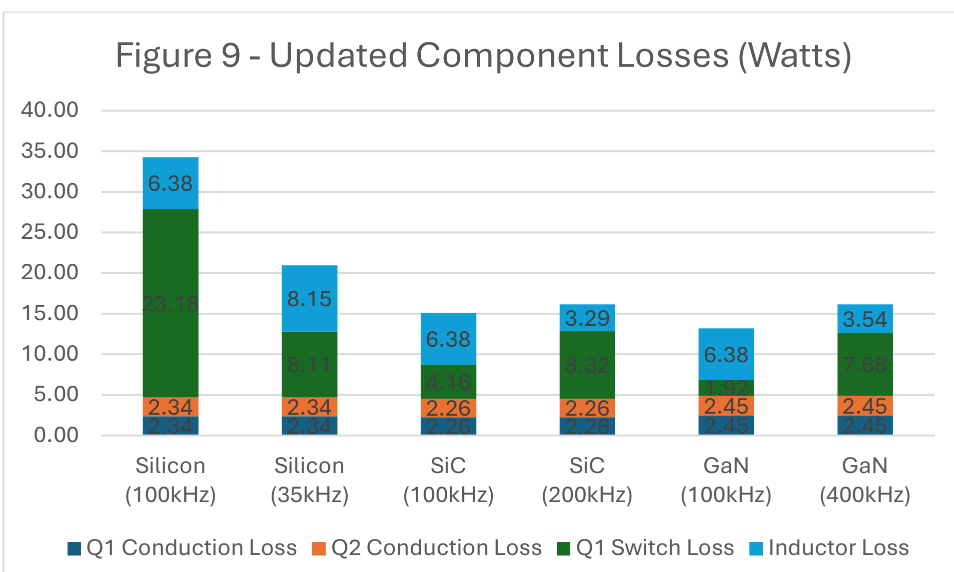
With a baseline established, the switching frequency of each design can then be adjusted to limit the maximum power dissipation in Q1 to 10.5 watts or less and the circuit capacitors and inductors can be optimized for the adjusted operating frequencies. The graph below shows the overall efficiency of the updated designs versus the 100 kHz baseline designs. In the updated designs, the Silicon operating frequency was reduced to 35 kHz, the SiC operating frequency was increased to 200 kHz, and the GaN operating frequency was increased to 400 kHz. This resulted in the overall efficiency of the Silicon design increasing substantially while the wide bandgap semiconductor designs decreased slightly in overall efficiency. However, the SiC and GaN designs are still more efficient overall. The net result is 16 watts of loss in Si design versus only 11 watts of loss in the SiC and Gan designs.



The chart below shows the updated Q1 power loss for each design versus the 100 kHz baseline design. As expected, the switching loss in the Silicon design decreased with the lower operating frequency and the switching loss in the SiC and Gan designs increased with the increase in operating frequency. The conduction losses stay unchanged as they are only a function of the output current and the part on-resistance. The design goal of limiting the power loss in Q1 to less than 10.5 watts for all three designs has also been achieved. There has been a 65% reduction in switching losses in the Si design and all three designs now have a Q1 loss of approximately 10.5 W.

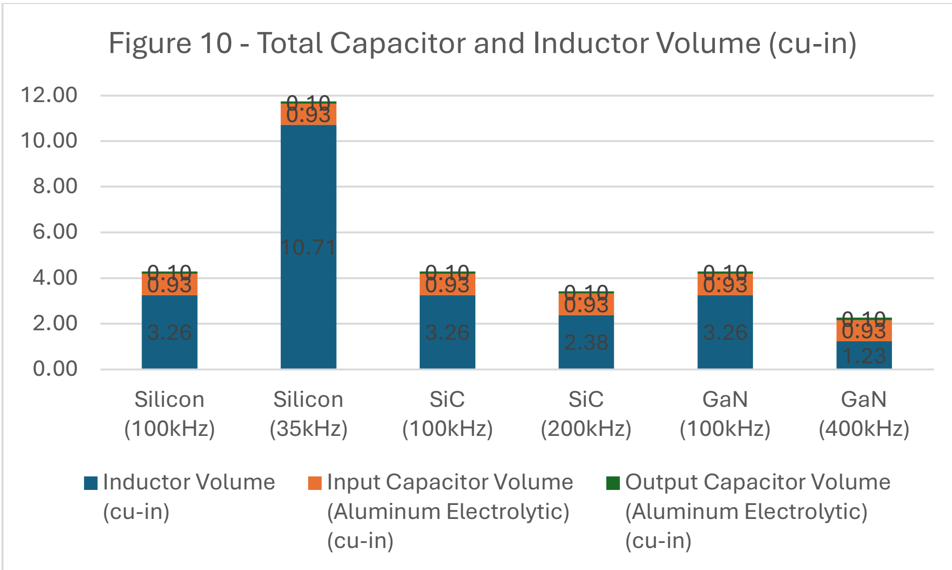



The graph below shows the total losses for the updated designs. Changing the operating frequency also resulted in updated losses in the inductor L1, and a lower loss core material was selected for the higher frequency designs to keep a similar power density. Since the converter's input and output voltage and current design requirements were unchanged, the required inductance in L1 is also directly proportional to the switching frequency. As the inductance increases or decreases the power loss increases and decreases respectively.



## Converter Size Comparison

The same buck converter design example can be used to show the effect of operating frequency on overall converter volume. The graph below shows the total volume in cubic inches of the input capacitors, the output capacitors, and the inductor for the buck converter design described above.




In the base 100 kHz design, all three converters occupy the same total volume of 4.29 in3 and all three designs use identical output inductors, input capacitors, and output capacitors. After the operating frequency of the designs was adjusted based on controlling the Q1 power loss, the effects of operating frequency became clearer. The Si converter now occupies 11.74 in3 while the SiC and GaN designs only occupy 3.41 in3 and 2.26 in3 respectively. The Si converter is 3.5 times larger than the SiC converter and 5 times larger than the GaN converter.

All the volume reduction in size came from the increased operating frequency and the resulting decrease in the inductor size. However, additional reductions in volume are possible with the higher frequency converters by changing the input and output capacitor type. The required input capacitance is a function of the input current, desired input ripple voltage, and the switching frequency. The required output capacitance is a function of the output current, desired output ripple voltage, and the switching frequency. With higher frequency, the required capacitance decreases. When selecting the input and output capacitors, they must not only meet the minimum calculated capacitance, but they must have a voltage rating higher than the working voltage and a ripple current rating higher than the expected ripple current. Additionally, the output capacitor must meet the required ESR (equivalent series resistance) for the desired output voltage ripple and dynamic response. As a result, the minimum required capacitance isn't always the main selection criteria.

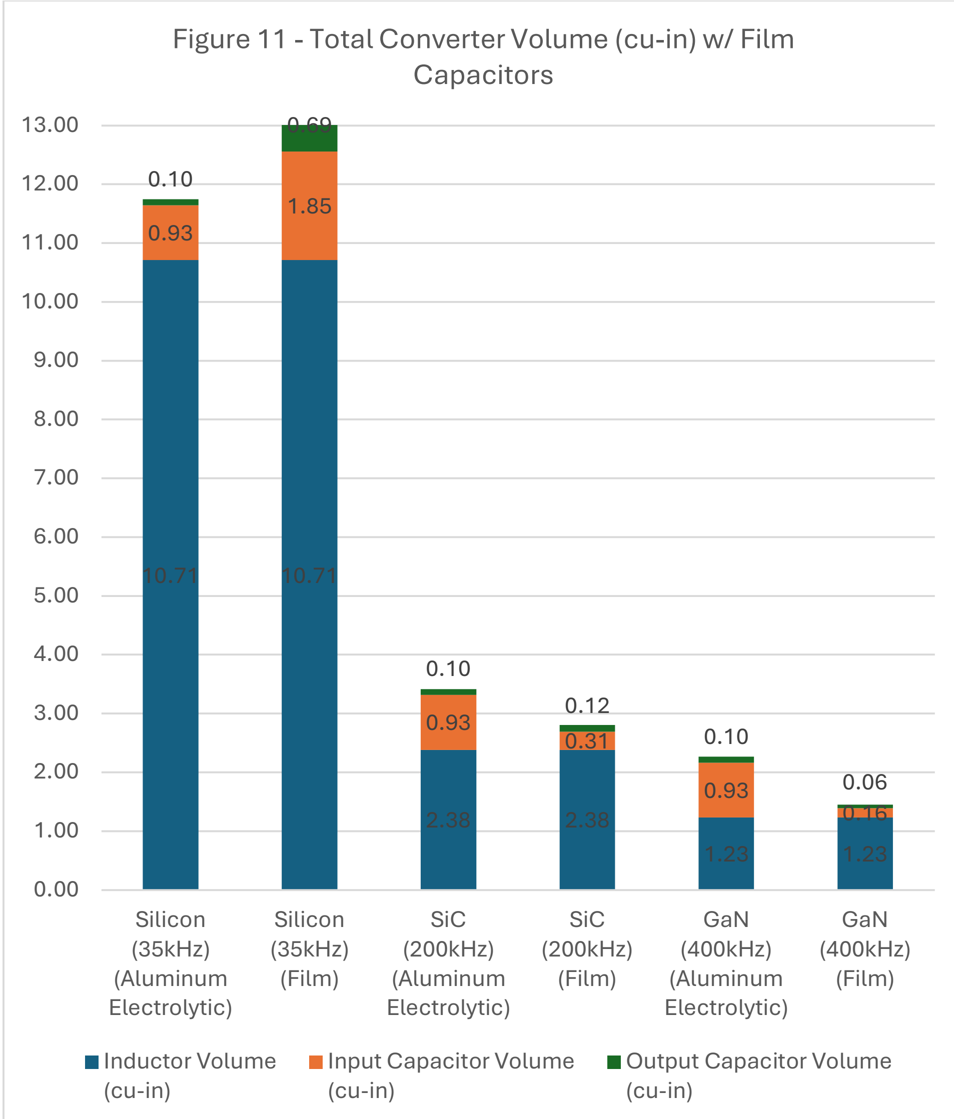
All the designs shown above use aluminum electrolytic capacitors which offer high energy storage density (higher capacitance) at a relatively low overall cost. However, as the switching frequency increased and the required capacitance decreased, there was no reduction in the input and output capacitor volume as multiple aluminum electrolytic capacitors were still required to stay under the ripple current rating of each capacitor. As an alternative, a film capacitor can be used. Film capacitors offer lower energy storage density (lower capacitance) but offer a higher ripple current rating at a higher cost. The table below shows the tradeoff between capacitance and ripple current rating versus cost.

| **Capacitor Type** | **Per Joule (Capacitance)** | **Per Ripple Current Amp** |
|---|---|---|
| Aluminum Electrolytic | $0.05 – $0.10 | $3 |
| Film | $0.20 – $0.50 | $1 |

Table 3 - Capacitance and Ripple Current Rating versus Cost

The graph below shows the total converter volume if the aluminum electrolytic capacitors are replaced with film capacitors. While the inductor volume still dominates, the total volume for the SiC converter has been reduced another 20% to 2.81 in3 and the GaN converter has been reduced by 36% to 1.45 in3. At the same time, the Si converter has increased in volume by 13% to 13.25 in3. The Si design benefits from the high energy density of the aluminum electrolytic capacitors while the SiC and GaN benefit from the high ripple current rating of the film capacitors.

With each converter optimized for total size by adjusting the switching frequency and capacitor type, the volume differences are dramatic. The optimum Si converter using aluminum electrolytic capacitors at 35 kHz is 4.2 times larger than the optimum SiC converter and 8 times larger than the optimum GaN converter. Furthermore, none of the volumetric calculations include the required heatsink sizes. As discussed above, the Si design loses an additional five watts versus the SiC and GaN design in this 1,000 W example. As the converter power increases, the heatsink size required to cool the additional power losses becomes significant. The reduction in physical size also drives system level cost reductions through smaller heatsinks and physical enclosure sizes.




## Dynamic Response

The design example above establishes that the wide bandgap SiC and GaN converters can operate at higher frequencies with lower storage capacitance and inductance values versus Si converters. With higher frequency operation, energy is delivered in smaller chunks but more often. During a load step-up, the output of the converter will undershoot as the stored energy in the inductors and capacitors is depleted. In response, the converter increases its duty cycle to maximum to put more energy into the storage inductors, capacitors, and the load. Despite a lower frequency converter having more stored energy to initially deliver the increased load, the undershoot time is dominated by the loop response time which is proportional to the switching frequency. During a load step-down, the output voltage will overshoot, and the converter stops switching until the output voltage falls below its target value. Since a higher frequency converter has less stored energy, the energy will be depleted more quickly than a lower frequency converter having larger storage inductors and capacitors. This results in the higher frequency SiC and GaN converters having faster dynamic response times with less overshoot than Si converters.

## Wide Bandgap Semiconductor Market Application

The figure below was taken from the Navitas website from an article entitled Introduction to Wide Bandgap Semiconductors to illustrate the wide market application of both SiC and GaN devices. SiC devices, with their high thermal conductivity, are replacing IGBT and thyristor designs in medium to higher power applications (greater than one megawatt) with switching frequencies up to about 500 kHz. GaN devices are replacing standard Silicon and Super Junction Silicon devices in low to medium power applications at switching frequencies greater than 1 MHz.

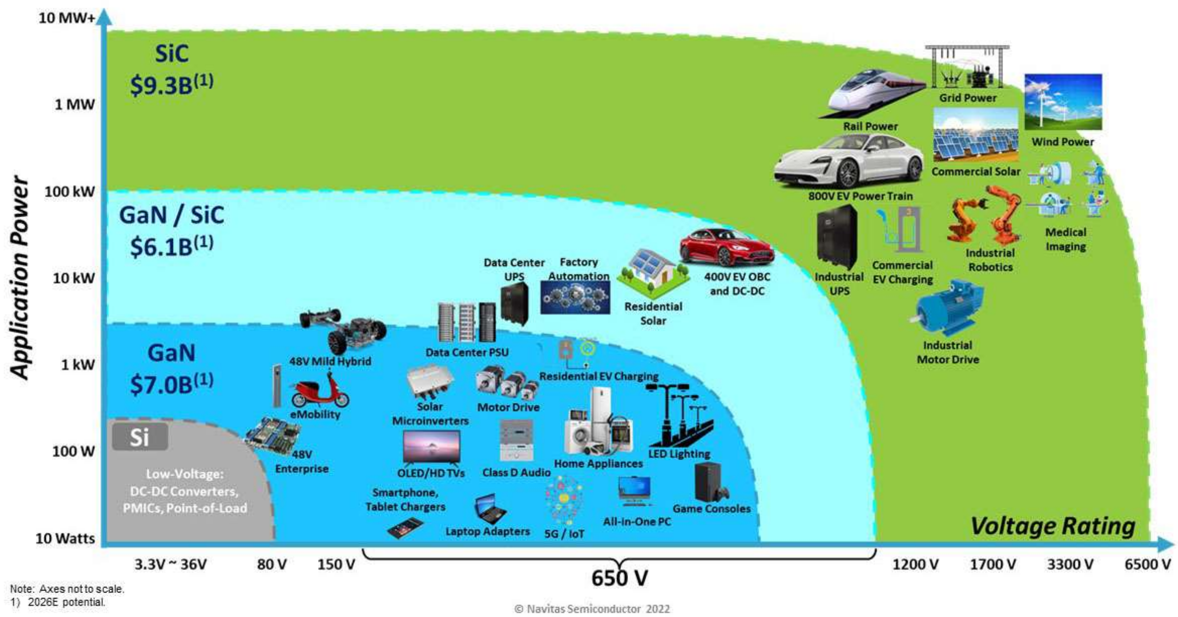



Figure 12 – Application of Wide Band Gap Semiconductors

SiC and GaN devices are already used in large data centers, utilities, power storage applications, and electric vehicles across the globe. Their use is driven by the need for more power in less space with lower operating costs (higher efficiency).

## Field Observed Reliability: Wide Bandgap Semiconductor-equipped Charger vs SCR Charger

The illustration below compares field failure experience over the life of two different battery charger platforms. The first is a simple analog-controlled 24 Volt battery charger employing a phase-controlled thyristor (SCR) power single-phase power train. The second is a 24 Volt, 450 Watt high frequency battery charger employing a wide range ac input boost converter, followed by a 400 Volt to 24 Volt dc-dc converter.

Both battery chargers were designed and built by the same company, using similar design practices and component derating guidance. The SCR charger first sold in 2002. The high frequency charger first sold in 2016.

Estimated failure rate based on parts count predicts that the SCR charger would materially outperform the high frequency charger.

The field observed rate of failure, however, is surprising. After the same number of months in production the field observed failure rate of the high frequency charger is nearly identical to the much simpler SCR charger. Even more surprising is that the rate of hardware failure (subtracting all firmware-related product failures) of the high frequency platform is even lower than the SCR charger at the same point in its production life.

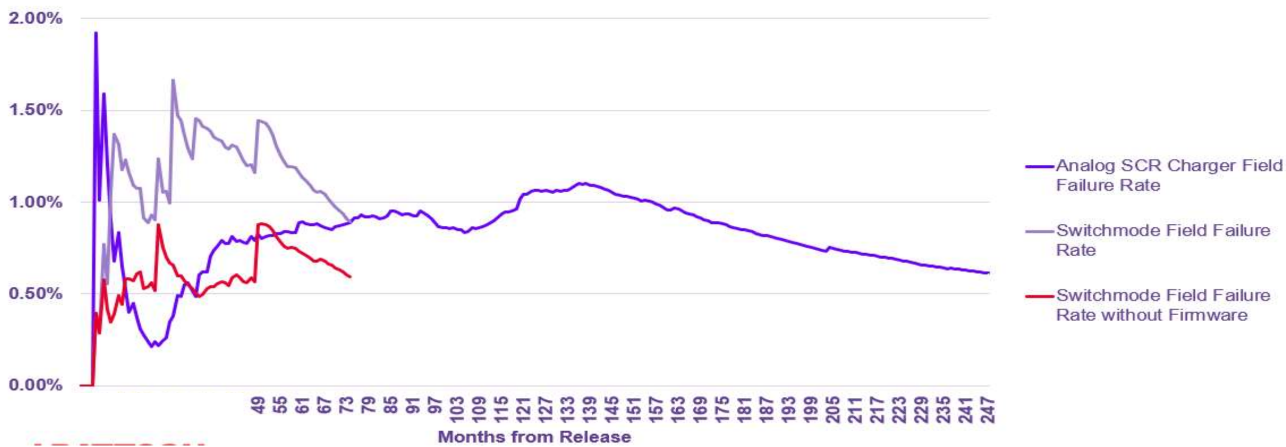



Figure 13 – Battery Charger Field Observed Reliability Comparison[1]

## Summary

The case for using wide bandgap devices, specifically SiC and GaN, is compelling. Wide bandgap semiconductors can operate at higher junction temperatures resulting in better overall system reliability and higher power density. Parts are available with higher breakdown voltages with lower on-resistance which greatly enhances performance in high power and high voltage applications versus traditional Si devices. They can operate at much higher frequencies making possible more compact, less costly designs with faster dynamic response. They offer proven reliability in harsh environments, and the costs are steadily falling as volumes increase. At the same time, they offer higher efficiency with lower operating costs.

[1] Switchmode Basic – Our Story, William Kaewert, Battcon 2023

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