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Exploring Gallium Nitride as a Viable Replacement for High Power and Performance Semiconductors: A Comparative Study of Electrical Properties and Fabrication Techniques

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Abstract

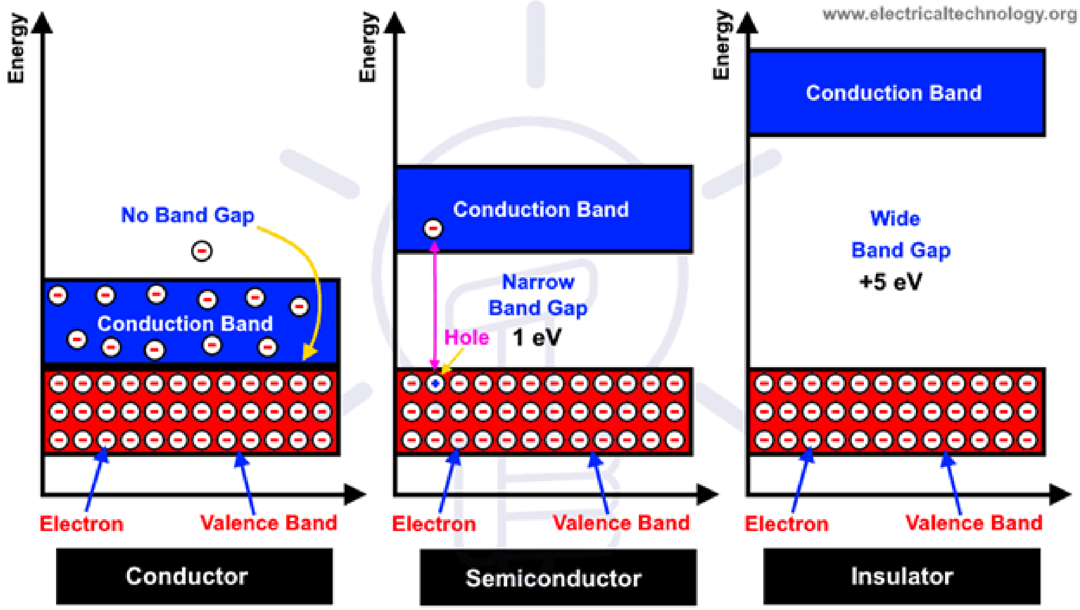
The semiconductor industry is continuously seeking to develop more compact, faster, and less expensive transistors allowing for more power to be packed into the same chip. This requires the development of smaller and more efficient semiconductors that are currently in the range of around 5-7 nanometers each. However, the limitations of silicon, the leading semiconductor material, are becoming more apparent, prompting exploration of other compounds, with a very promising candidate being gallium nitride (GaN). This paper presents an overview of GaN-based high electron mobility transistors (HEMTs) and integrated circuits (ICs), which offer several advantages over silicon-based counterparts. GaN HEMTs have lower on-resistance, faster devices, less capacitance, and less power consumption allowing them to sustain higher voltages and faster current. Meanwhile, GaN-based ICs have the potential to improve the efficiency of power conversion systems and circuits due to their ability to integrate both power-level and signal-level devices on the same wafer. With GaN-based devices, power conversion can become more efficient and cost-effective, ushering a new era for power conversion.

Semiconductors: An Essential Component of Our Lives

Semiconductors have played a massive part in technological development since 1901, when the first pragmatic application in electronics was discovered. Starting their journey off as a cat's-whisker detector used in early radio receivers to becoming the backbone of almost all technology, semiconductors have changed how we now live.

Semiconducting Properties

Semiconductors have unique properties that respond differently to electrical currents. It is classified as a material with lower resistance to electrical flow in one direction. Semiconductor materials have conductivities that fall between an insulator and a conductor. They are poor conductors with the ability to control concentrations of electrons.



There are naturally occurring semi-conducting substances, or “intrinsic” semiconductors, with extremely low electron and hole concentrations that rely purely on thermal or optical stimulation of electrons away from their valence bands to become mobile across the conduction band. One example is the column of group IV solids (C, Ge, Si, and Sn). Though, undoped or naturally occurring semiconductors are just poor electrical insulators that carry electricity. Doping which consists of adding either Group III or Group V atoms to an intrinsic semiconductor, is the conventional way of creating semiconductors, for example, doping carbon (group IV) with arsenide (group V). Doping allows us to vary the number of electrons and holes in semiconductors creating N-type materials (negative charge) when group IV atoms are doped with group V atoms and P-type materials (positive charge) when group IV atoms are doped with group III atoms.

Most semiconductor materials have four valence electrons and four electrons in the outer shell. However, a semiconductor gains interesting properties by putting one or two percent of atoms with five valence electrons, such as arsenic, with a four valence electron semiconductor such as silicon. A doped semiconductor is much more like a conductor than an undoped semiconductor. You can also dope a semiconductor with three-electron atoms, such as aluminum. The aluminum fits into the crystal structure, but now the system is missing an electron. This is called a hole. Making a neighboring electron move into the hole is like making the hole move. Putting an electron-doped semiconductor (n-type) with a hole-doped semiconductor (p-type) creates a diode. Other combinations develop devices such as transistors.

This makes these “extrinsic” semiconductors quite valuable since interesting properties are created once you have different dopings in differently doped semiconductors in the same device. This includes several other machines such as FETs, LEDs, CCDs, integrated circuits, and many more, as they can all be created depending on the properties of the P and N-type materials.

These semiconductors are primarily used to manage the flow of electric current in electronic equipment and devices, allowing them to be used in almost every machine we see today.

Commonly Used Semiconductors

Silicon and germanium, as well as the compounds gallium arsenide, lead sulfide, or indium phosphide, are among the most popular semiconductor materials. Even specific polymers have the potential to be semiconducting, enabling flexible, moldable plastic light-emitting diodes (LEDs).

Silicon, germanium, and gallium arsenide are the most common semiconductor materials. Germanium containing four valence electrons was one of the first semiconductor materials to be utilized.

The number of valence electrons present determines the conductivity of semiconductor material. While germanium was a crucial stage in the history of semiconductor materials, it has mostly fallen out of favor of silicon, the current most abundantly used semiconductor material.

Since the 1950s, silicon has been widely used as a semiconductor material. Silicon, the second most prevalent element on Earth after carbon, contains four valence electrons and melts at a greater temperature than germanium (1,414 degrees Celsius against 938.3 degrees Celsius for germanium). Not only is it the most common element on our planet, making it very cheap, but it is also a highly pure semiconductor with superior physical and technological properties compared to other semiconductor materials. Furthermore, silicon is a very stable atom with low resistance that resists breaking at high temperatures. Silicon extraction, purification, and crystallization processes are very effective and affordable. Silicon crystals have significant mechanical qualities because the element crystallizes in a diamond shape, which creates a relatively strong connection making it the best semiconductor to date.

The second most popular semiconductor now in use is gallium arsenide. Gallium arsenide, which contains three valence electrons in gallium and five in arsenic, is a compound rather than an element, in contrast to silicon and germanium.

Gallium-arsenide devices respond swiftly to electric impulses thanks to their eight valence electrons, which makes the material ideal for boosting the high-frequency transmissions observed in television satellites. However, gallium arsenide has several drawbacks: the material is more challenging to mass-produce than silicon, and the chemicals employed in gallium arsenide synthesis are very toxic.

Many semiconductors that have recently been innovated include:

Gallium Nitride: Due to its sizeable critical energy field, high-power gallium nitride might be employed for quicker, more compelling power conversions in electric grid systems.

Antimonide-bismuthide-based semiconductors: Semiconductors with antimonide and bismuthide bases are used to create better-infrared sensors for the military and medical fields.

Graphene: Although full commercialization of graphene might take up to 25 years, it has the potential to overtake silicon as the most versatile semiconductor material.

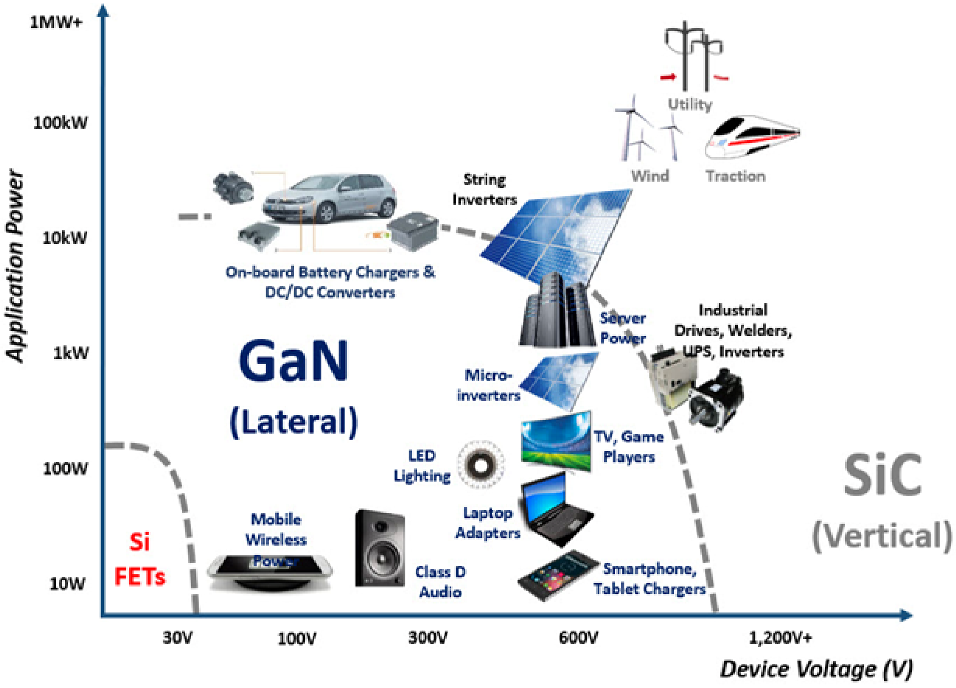
Pyrite: The rare earth metal cadmium telluride, used extensively in solar cells but has a finite supply, might be replaced by pyrite. Pyrite is widely available, affordable, and non-toxic.

Despite being the primary component in semiconducting manufacturing throughout the majority of the late 20th and early 21st centuries, silicon is nearing the end of its time. Industry experts are concerned that silicon may soon meet the boundaries of Moore’s Law (the principle that the speed and capability of computers can be expected to double every two years due to increases in the number of microchip transistors contained) due to the need for ever-smaller microchip transistors. These quicker integrated circuits have nearly reached the maximum efficiency of the material. This is why research into new semiconducting materials such as gallium nitride is essential and needs to be continued.

Gallium Nitride

Gallium Nitride is one of the upcoming innovations in semiconductors that has the potential to replace silicon as the king of semiconductors. Gallium nitride (GaN), made by combining gallium (atomic number 31) and nitrogen (atomic number 7), is a wide bandgap semiconductor for high-efficiency power transistors and integrated circuits. Its 3.4 eV bandgap and a wurtzite type structure have been the material used for making blue light-emitting diodes (light-emitting devices that can withstand corrosive environments) since the 1990s.

The bandgap is the energy required to liberate an electron from its orbit around the nucleus, and gallium nitride's bandgap is more than three times that of silicon, thus the moniker 'wide' bandgap or WBG.



Gallium nitride's greater bandgap, which defines the amount of electric field a material can endure, makes it possible to create semiconductors with very short or narrow depletion zones, which results in device structures with extremely high carrier densities. Speeds up to 100 times faster are made possible by ultra-low resistance and capacitance, which are made possible by considerably smaller transistors and shorter current routes.

It is becoming more relevant because of its capacity to provide noticeably better performance across various applications while using less energy and physical space compared to conventional silicon technologies. Gallium nitride technologies are becoming critical in some applications where silicon power conversion has reached its physical limits. In others, the advantages of efficiency, switching speed, compactness, and high-temperature operation combine to make GaN increasingly appealing. It is already the top contender for enhancing electronic performance and reactivating Moore's Law's positive momentum. It is already commonly known that GaN can conduct electrons more than 1000 times more effectively than silicon while also being produced at a cheaper cost than silicon.

If GaN becomes our primary semiconductor used in the industry today, we could see many improvements such as:

- lower on-resistance giving lower conductance losses
- faster devices yielding less switching losses
- less capacitance resulting in fewer losses when charging and discharging devices
- less power is needed to drive GaN circuits
- smaller devices taking up less space on the printed circuit board
- lower cost

An Eco-Friendly Semiconductor

Not only is GaN much more efficient than many semiconductors to date it also has the potential to be widely used as a component in green technologies across the world. A switch to GaN technology will satisfy demand while reducing carbon emissions as the world's energy needs grow. It has been demonstrated that the design and integration of GaN may provide next-generation power semiconductors with a carbon footprint that is ten times smaller than that of slower, older silicon chips. A global Si-to-GaN data center upgrade is predicted to cut energy loss by 30–40%, translating to over 100 TWhr and 125 Mtons CO$_2$ savings by 2030. GaN has also been proven by researchers from North Carolina State University and Purdue University to be non-toxic and compatible with human cells, paving the way for its usage in various biomedical implant technologies.

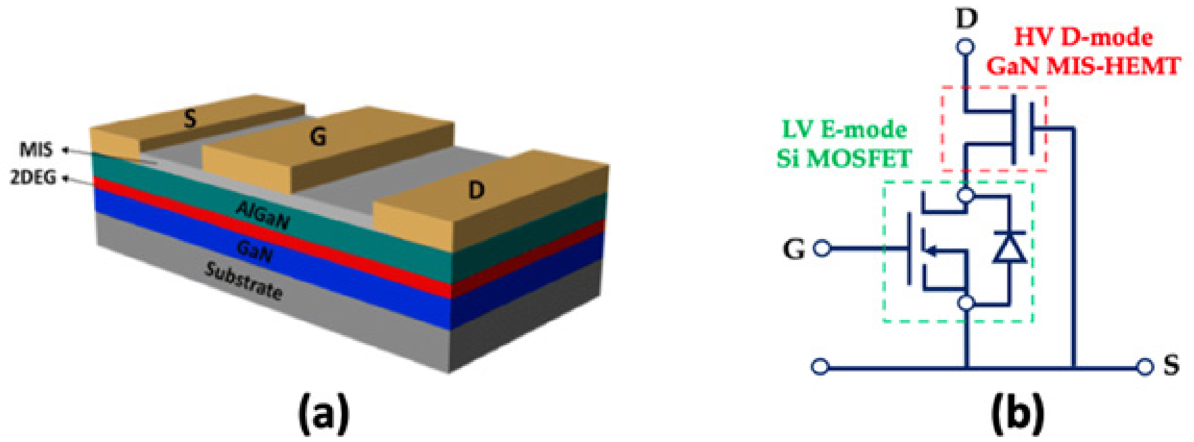
GaN Power Transistors

One of the most prominent applications for GaN includes power transistors or, more specifically, High electron mobility transistors (HEMTs).

Power design experts have been searching for the ultimate switch—one that can quickly and effectively transform unprocessed electrical energy into a regulated, beneficial flow of electrons—since the advent of the electronic era more than a century ago. Vacuum tubes were the first, but their limited usage was due to their inefficiency, demonstrated by the heat they produce and their huge size and expensive cost. The transistor then became widely used in the late 1950s; with its compact size and improved efficiency, it was seen to be the “holy grail” and quickly replaced tubes while opening up vast new markets that vacuum tube technology was unable to penetrate.

Building upon that, in 1980, a high electron mobility transistor was introduced. A field-effect transistor with high electron mobility (HEMT) uses a heterojunction, or the intersection of two materials with differing band gaps, as the channel rather than a doped area (as is generally the case for a MOSFET). GaAs and AlGaAs are two materials that are frequently combined; however, there are many variations depending on the device’s intended usage. Gallium nitride HEMTs have gained interest recently because of their high-power performance, whereas devices integrating more indium often exhibit higher high-frequency performance. HEMTs serve as digital on-off switches in integrated circuits, just as regular FETs. A small voltage can be utilized as a control signal to employ FETs as current amplifiers for enormous quantities of current. The distinctive current-voltage properties of the FET enable both of these applications. HEMT transistors are utilized in high-frequency goods, including mobile phones, satellite television receivers, voltage converters, and radar equipment, because they can function at higher frequencies than regular transistors, up to millimeter wave frequencies. They are commonly employed in low-power amplifiers, satellite receivers, and the defense sector.

Compared to comparable silicon-based alternatives, GaN-based HEMTs usually paired with indium have a quicker switching speed, excellent thermal conductivity, and lower on-resistance. Due to these characteristics, a wide range of power conversion systems may be made more efficient, smaller, and cheaper using GaN transistors and integrated circuits.



GaN Integrated Circuits

Another leading potential application of GaN includes integrated circuits (ICs).
Modern electronics rely heavily on ICs. The majority of circuits have these as their brain and heart. They are the commonplace little black “chips” on almost all circuit boards.

The term IC refers to an assembly of electronic components that are manufactured as a single unit and comprise miniature active devices (such as transistors and diodes) and passive devices (such as capacitors and resistors) as well as their interconnections (typically silicon). Thus, the final circuit is a tiny monolithic “chip,” which may only be a few square millimeters or a few square centimeters in size. The size of the individual circuit components is often tiny.

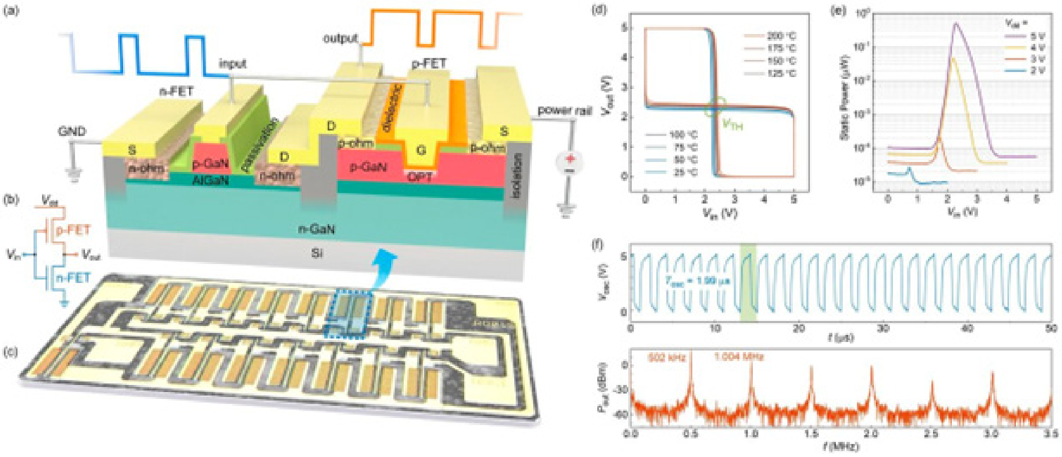
In 1947 it was discovered that, given the right conditions, electrons would create a barrier at the surface of certain crystals. They learned how to manipulate this barrier to regulate the flow of electricity through the crystal. The scientists developed a device that could carry out several electrical functions, such as signal amplification, that were previously carried out by vacuum tubes by controlling electron flow via a crystal. This created the IC, a grouping of electronic components—resistors, transistors, capacitors, etc.—connected in series to accomplish a single task.

GaN’s ability to incorporate both power-level and signal-level devices on the same wafer presents the most possibility for it to influence the efficiency of power conversion systems and integrated circuits in the near future.

In 2014, monolithic half-bridge devices, the first commercially available GaN ICs from EPC, debuted. As technology advanced, more complicated integration became available on the market, such as a device that incorporates two power transistors and driver circuitry that permits effective operation up to 7 MHz when driven by a low power logic gate.

In 2020, a monolithic half-bridge with driver and level shift circuitry was developed to produce a monolithic power stage. The EPC2152 IC will be followed by a series of monolithic power stage devices with best-in-class performance and application-specific capabilities, ushering in a new era for power conversion.

Discrete technology and integrated circuits will converge in a few years. It will become impossible to extract the current in and out of the bumps and bars on discrete devices as they reach ever-higher power densities. Integration into compact, multi-chip, multi-function integrated circuits will thus be required. Discrete transistors in power conversion are expected to become obsolete over the next few years slowly, and designers will increasingly use integrated solutions when creating power systems.



Creating Power

The primaries used for GaN lie in high-efficiency power transistors and integrated circuits. GaN produces power in these devices by creating a strain at the interface by growing a thin layer of aluminum gallium nitride (AlGaN) on top of a GaN crystal, which results in the induction of a compensating two-dimensional electron gas (2DEG).

A 2DEG is a scientific model utilized in solid state physics that allows an electron gas to move freely in two dimensions while firmly confined in the third. When electrons are restricted to an interface between two distinct materials, a 2DEG occurs. For motion in the third direction, these close quarters create quantized energy levels that may subsequently be disregarded for most issues. As a result, the electrons seem to be a 2D sheet enclosed in a 3D environment. Two-dimensional hole gas (2DHG) is the name given to the similar construct of holes, and such systems have a variety of beneficial and intriguing characteristics. This 2DEG is primarily found in gallium nitride and other semiconductors in transistor-like substances.

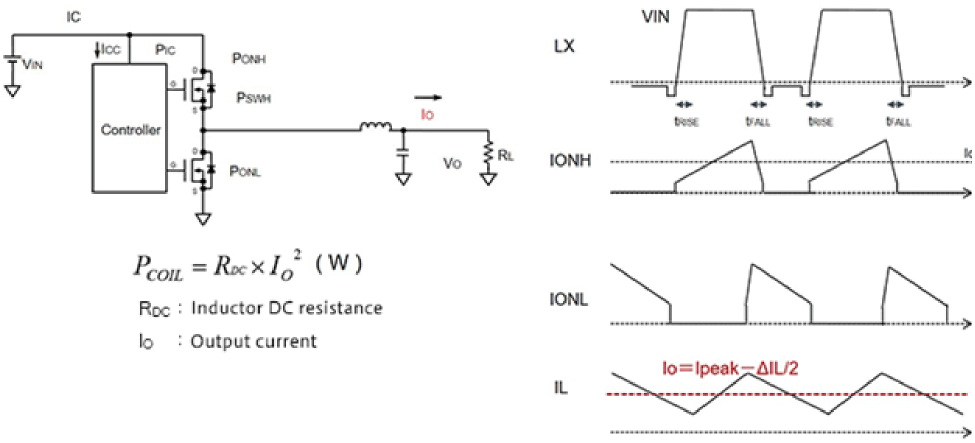
An electric field is then placed over this 2DEG allowing for electrons to be conducted. Due to the electrons being confined to a relatively tiny area at the contact, this 2DEG is highly conductive. From roughly 1000 cm2/Vs in unstrained GaN to between 1500 and 2000 cm2/Vs in the 2DEG region, this confinement improves the mobility of electrons.
Thus, because of its high mobility, transistors and integrated circuits with better breakdown strength, quicker switching speed, higher thermal conductivity, and lower on-resistance than similar silicon solutions are produced.

Gallium Nitride, as well as Silicon Carbide, also has a much wider bandgap than other semiconductors. Gallium nitride has a bandgap of 3.4 eV compared to silicon MOSFETs. GaN can also be used in high-power and high-frequency optoelectronic devices.

Improving Efficiency

Efficiency in semiconductors is determined by the power lost in a power supply. One of the leading causes of power loss in a power supply is power transistors. Conduction losses are generated by current flow, whereas switching losses happen when a transistor switches from being on to off.

In complete conduction, the gadget experiences conduction losses. The voltage at the device's terminals is the voltage drop caused by the device itself, and the current in the device is whatever the circuit requires. The duty cycle and these losses are closely related. Power semiconductor conduction losses are frequently computed by connecting an ideal machine in series with a voltage UF representing the voltage drop and a resistor Ron describing the current dependence. A straightforward model for the current-voltage dependency's non-linear property is developed in this manner.

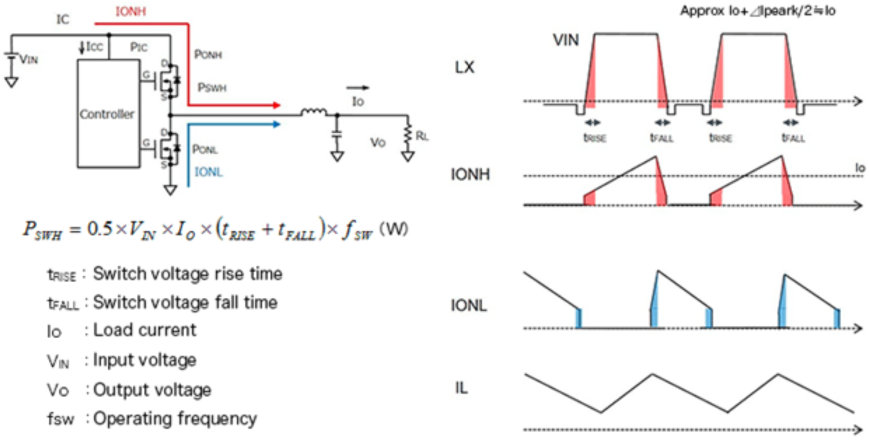


$$P_{COIL} = R_{DC} \times I_O^{\,2} \ \text{(W)}$$

R_{DC} : Inductor DC resistance

I_O : Output current

When a device switches from the blocking state to the conducting state and vice versa, switching losses take place. This period is defined by multiple voltages between its terminals and a significant current flowing through it. The energy lost during each transition must be multiplied by the frequency. Switching losses make up a sizable portion of the overall system losses in power electronics. As a result, there may be significant inaccuracies in the total losses if switching losses are not considered in the computation or if the conduction losses are weighted with an approximated factor to account for switching losses. To increase design dependability, it is crucial to quantify the switching losses precisely if one intends to determine the junction temperature time behavior.



$$P_{SWH} = 0.5 \times V_{IN} \times I_O \times (t_{RISE} + t_{FALL}) \times f_{SW} \ \text{(W)}$$

t_{RISE} : Switch voltage rise time

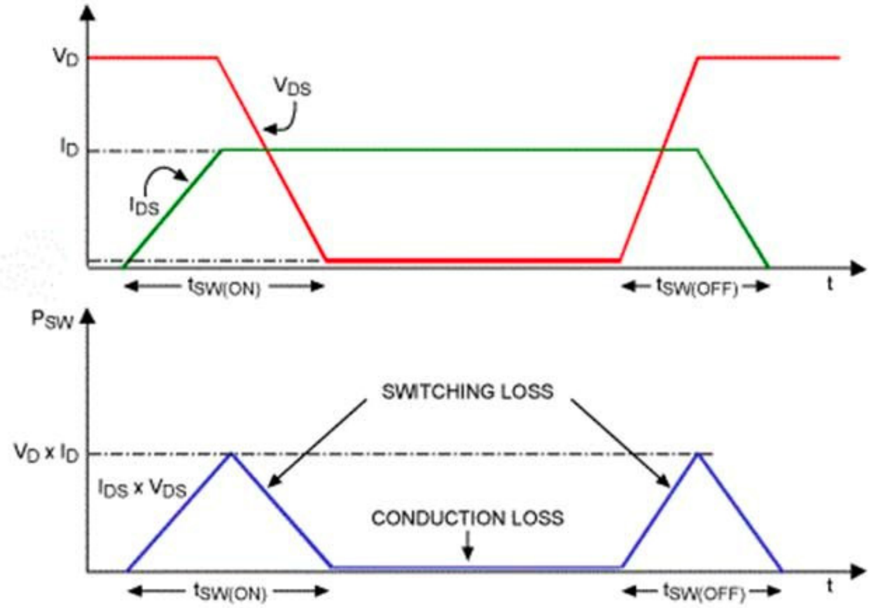
t_{FALL} : Switch voltage fall time

I_O : Load current

V_{IN} : Input voltage

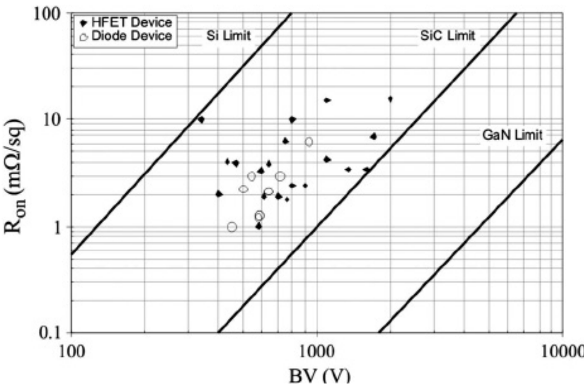
V_O : Output voltage

f_{SW} : Operating frequency



Conduction Losses

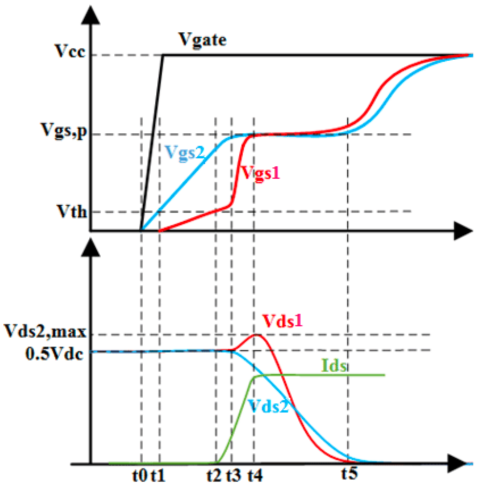
Conduction losses in GaN transistors are proportional to the resistance known as Ron between the drain and source when turned on, much like in silicon transistors. GaN and other WBG materials link between breakdown voltage and Ron is a fundamental advantage. This relationship's potential upper and lower bounds for silicon, gaN, and silicon carbide (SiC), another WBG material, are depicted in the picture below. As shown, the Ron of the WBG devices is significantly lower than that of silicon for a given breakdown voltage, with GaN having the most deficient Ron among the three. Adopting GaN and other WBG materials becomes required if Ron advancements continue, as silicon is getting close to its theoretical limit.



Breakdown voltage and the theoretical limits of Ron for Si, GaN, and SiC transistors

Switching Losses

Utilizing GaN also results in a decrease in switching losses in addition to reductions in conduction losses. Switching losses are caused by various reasons, some of which are reduced by using GaN. As seen in the picture below, one loss mechanism is brought on by the fact that a transistors current starts to flow before the voltage between the drain and source drops. During this period, there are significant losses (equivalent to the volt-amp product). The losses experienced during this transition can be decreased by speeding up the switches on/off shift. GaN transistors can lessen this transition's losses since they can switch on faster than silicon transistors.



Waveforms of the drain voltage and current during the switching transition

GaN also decreases switching loss by not utilizing a body diode. A half-bridge has a time known as the "dead-time," where both switches are off to prevent a short circuit scenario. Although electricity is still flowing since both switches are off, it is being driven via the body diode. When a silicon transistor is turned on, the body diode is far less effective than the Ron resistance. GaN transistors do not have body diodes. The Ron resistance conducts current that would typically pass through the body diode of a silicon transistor. The losses sustained during the downtime are significantly decreased as a result. Because a silicon transistor's body diode conducts during the dead-time, it must be switched off when the other switch is turned on. During this period, while the diode shuts off, current flows in the other direction, incurring further losses. The lack of a body diode in a GaN transistor leads to near low reverse recovery losses. This results in lower switching loss-making GaN transistors more efficient.

Even though switching losses only last for brief durations throughout the switching period, it is nevertheless beneficial to look at them on average. The average value can be retained at a safe level even if there may be significant losses during a single switching transition if the time interval between switches is long (i.e., there is a low switching frequency). GaN's lower switching losses raise the switching frequency by shortening the time between switches. Numerous significant components (including the transformer, inductors, and output capacitors) may be smaller thanks to the higher switching frequency.

GaN ICs in Chargers

Semiconductors are very versatile materials; it will be a while before they completely overtake silicon. Still, it has already made its way into several applications, such as chargers.

If we use a phone or laptop charger, the low resistance and capacitance made possible by GaN technology translate to improved charging efficiencies, allowing for quick battery charging (instead of burning up that energy as heat which warms the charger). Faster switching also enables the charger to significantly reduce the size and weight of the energy-storing passive components, allowing for more power delivery to the battery (as they store much less energy in each switching cycle). These GaN Power ICs enable designers to reduce the size of the main transformer, EMI filter components, output capacitors, and bulk capacitors, in addition to minimizing the size of the power semiconductor itself by supporting greater power densities and switching frequencies. It creates a "Manhattan skyline" of tall and short components connected to a primary printed-circuit board as specific components decrease (PCB). This also creates significant air gaps around the smaller pieces providing room for 3D material innovations for mechanical designs that maximize power density in the future.

A gallium nitride power IC monolithically combines control, protection, and drive with GaN power (FET) and drive in a single SMT package. These GaNFastTM power ICs are transformed into simple-to-use, quick, effective "digital-in, power-out" building blocks. Due to the gate drive loop's almost minimal impedance, integration allows for virtually little turn-off loss.

For a designer, "ease-of-use" translates into "rapid prototyping" and "maximizing first-time-right" ideas very quickly, while "robust, high-quality performance" translates into "short qualification time." These variables accelerate time-to-market and time-to-revenue metrics.

GaN fast chargers have already been sold by several companies, which include Belkin, Anker, AUKEY, Hyper, and Baseus, as well as tier-1 OEMs including Dell, Lenovo, Samsung, Xiaomi, LG, and OPPO.

Advantages of GaN Vs. Other Semiconductors

Gan has many advantages over silicon and other semiconductors.

Lower energy costs: GaN semiconductors are intrinsically more efficient than silicon, which means less energy is lost as heat, and thus system sizes and material costs are reduced.

Greater switching frequency: Power circuits may employ smaller inductors and capacitors due to the higher switching frequencies offered by GaN devices. The inductance and capacitance drop directly to the frequency; for every 10X rise, the capacitance and inductance are reduced by 10X. This can lead to a significant reduction in weight, volume, and expense. In motor driving applications, the greater frequency can also mean less acoustic noise. High frequency also allows for greater spatial flexibility, larger transmit to receive airgaps and wireless power transmission at higher powers.

Reduced system cost: Although GaN semiconductors usually are more expensive than silicon, using GaN results in lower system costs by decreasing the size and cost of additional components such as passive inductive and capacitive circuit elements, filters, cooling, etc. Savings are between 10 and 20 percent. Gallium nitride power amplifiers are perfect for microwave and terahertz (THz) devices, such as imaging and sensing, the aforementioned future market, due to their capacity to operate at significantly higher temperatures and voltages than gallium arsenide (GaAs) transistors.

Higher power density (the smaller volume): Higher switching frequencies and operational temperatures than silicon lead to smaller heat sinks, the move from liquid to air cooling, the elimination of fans, and lower magnetics.

GaN vs. Si

In the 1970s, silicon swiftly replaced vacuum tubes as the preferred material for semiconductor transistors due to its fundamentally superior electrical characteristics and lower production costs. Silicon power MOSFETs have now hit the limit of their ability to provide higher performance at steadily decreasing costs, much like the vacuum tube. Fortunately, the search for the perfect switch with infinitely rapid switching speed, zero electrical resistance, and a reduced price has not diminished. New basic materials have arisen to construct integrated circuits and transistors capable of high-performance power conversion.

GaN has several physical qualities that make it clear why it has the potential to replace silicon. GaN is a semiconductor with a direct bandgap that is binary III/V and has a bandgap of 3.4eV, much higher than silicon's bandgap of 1.1eV.

The bandgap allows GaN device structures to have greater carrier densities and be packed extremely tightly because the material allows for strong electric fields, which permits depletion areas to be very short or narrow. For instance, a typical 650 V lateral GaN transistor has a drain drift area of 10-20 m, or around 40-80 V/m, and can withstand above 800 V. This is far more than silicon's theoretical limit, which is about 20 V/m. The bandgap limit of around 300 V/m is still far away, providing potential for future generations of lateral GaN devices to advance.

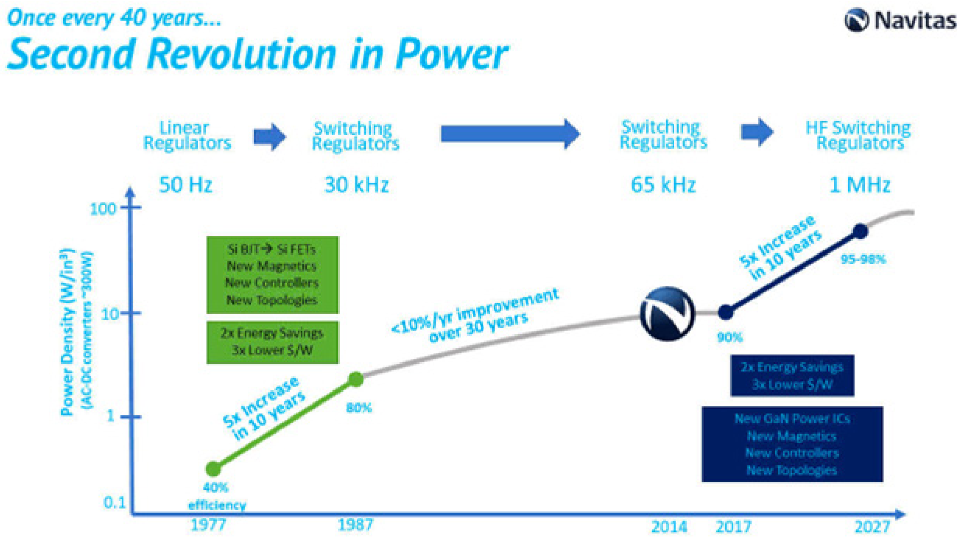
GaN is also ideal for optoelectronics for creating devices like UV LEDs where frequency doubling is unfeasible. GaN semiconductors not only have 1000 times the electron mobility of silicon but can also function at greater temperatures without losing their properties (up to 400 degrees Celsius). GaN would be particularly useful in situations with high frequencies (THz), high temperatures, and high power.

Depending on the implementation, the figure of merit produced from the product of gate charge (QG) and normalized on resistance (RDS(ON)) can be five to twenty times better than silicon. Switching rates can be up to 100 times quicker because of ultra-low resistance and capacitance made possible by significantly smaller transistors and shorter current channels.

Fortunately, because GaN devices are produced using conventional silicon manufacturing techniques in the same factories that currently produce traditional silicon semiconductors, and because the resulting devices are much smaller for the same functional performance, the cost to have a GaN device is inherently lower than the cost to build a MOSFET device. GaN devices usually cost less to create than their silicon equivalents because the individual devices are significantly smaller than silicon devices and can be made in far more significant quantities per wafer. The cost disparity widens even further as GaN technology advances.

GaN power ICs combine frequency, density, and efficiency benefits in half-bridge topologies such as active clamp flyback, totem-pole PFC, and LLC. Moving from hard- to soft-switching topologies may lower the general loss equation for the main FET by moving from hard- to soft-switching topologies, which improves efficiency at 10x higher frequencies.

Gallium nitride power ICs are the starting point for a second revolution in power electronics, thanks to their record-breaking performance.



GaN vs. GaAs

ICs, particularly monolithic microwave ICs, comprise most GaAs products (MMICs). Most of these MMICs are gain blocks with low signal levels. Some amplifier blocks employ pHEMTs, while others use HBTs or MESFETs. There are frequency bands up to 30 GHz. GaAs devices have a high-frequency cutoff (ft) or unity gain-bandwidth in the 150 GHz range, although there aren't many devices or IC amplifiers with that within. These MMICs are frequently utilized in the designs of most microwave equipment, including radios, satellites, radar, and electronic warfare items.

GaN is astounding because of its high power density or capacity to disperse heat from a compact container. GaN has a power density that ranges from 5 to 12 W/mm, while GaAs have a fundamental power density of around 1.5 W/mm. Because of its high electron mobility, Transistors often have fTs of up to 200 GHz. GaN can also do these tasks at high breakdown voltages, around 80 V.

GaN vs. SiC

Silicon Carbide (SiC) is a compound semiconductor made of silicon and carbide. Like GaN, it has the potential to replace silicon as the semiconductor used in most devices. SiC has several benefits over silicon, including three times the band gap and a range of p- and n-type control needed for device fabrication.

Both SiC and GaN are WBG materials that perform physically better than Si. GaN and SiC can withstand greater voltages than Si because their bandgaps are more significant than those of Si (1.1 eV), GaN (3.2 eV), and SiC (3.4 eV). GaN and SiC have breakdown voltages that are ten times greater than Si's (measured in MV/cm).

GaN and SiC differ primarily in speed or "electron mobility." GaN is the high-frequency winner because it is 30 percent faster than Si and 300 percent quicker than SiC at 2,000 cm2/Vs.

GaN On Si integration

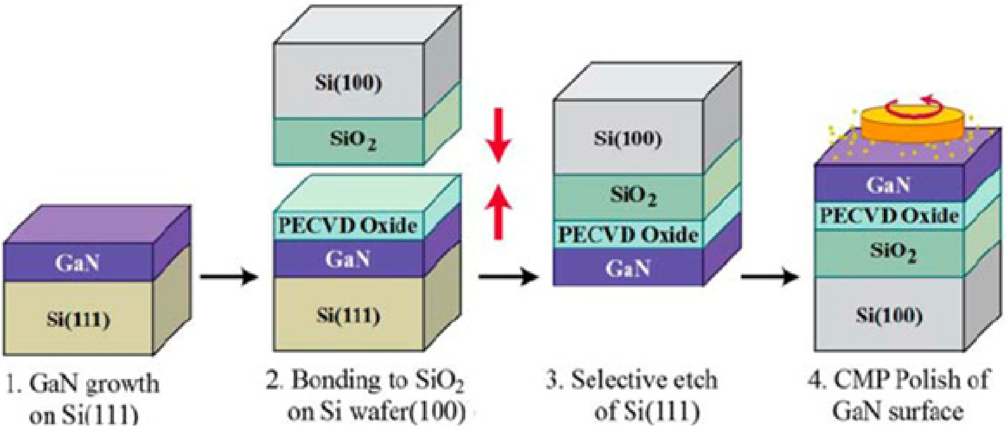
Every time a corporation thinks about making a substantial change to the architecture, parts, or suppliers utilized in the planning and producing its semiconductor-driven products, it must first make sure the performance provided is what was promised. After then, the requirement to verify costs and dependability emerges as the main issue.

GaN power transistors were first viewed as more expensive and less reliable than silicon for power supply, wireless power, and envelope tracking applications when they entered the market about ten years ago. GaN was much more costly on a primary transistor-to-transistor basis due to low-scale manufacturing and low yields. The industry was unsure of how to demonstrate the dependability of GaN devices because it was a new product. It wasn't apparent whether the JEDEC MOSFET test standard was suitable.

However, a recent breakthrough shows that we can significantly reduce the cost of GaN-based devices by growing GaN-based devices on SI.

Growing GaN-based LEDs on silicon wafers, easily accessible in large diameters (e.g., 150 mm or greater) and at a low price, could result in a more significant cost decrease. These wafers can also be used with current processing lines often employed in the electronics sector. Growing GaN on Si substrates presents several substantial technical obstacles, and many are working to find solutions to these problems.

Numerous substrates, including sapphire, silicon carbide, and silicon, can be used to generate gallium nitride crystals. A GaN epi layer must be grown on top of the silicon to utilize the existing silicon manufacturing infrastructure. This eliminates the need for expensive specialist production locations and generally uses accessible, inexpensive large, diameter silicon wafers.



GaN development on sapphire, SiC, or Si utilizes a seed layer or buffer layer to compensate for the lattice mismatch between the substrate and the epilayer. GaN development on substrates made of 6H-SiC, 4H-SiC, and 3C-SiC has been examined concerning the effects of surface pre-treatment with NH3 (Lee et al. 2000). The deposited GaN layer was discovered to be polycrystalline after SiC underwent nitridation. GaN that is epitaxial but island-like if TMG is pre-adsorption. In the third instance, GaN epilayers were effectively formed on SiC with an ultra-thin (15 nm) covering of AlN (by adsorption of TMA or by 50 s deposition of AlN). However, a 20–30 nm thick AlN seed layer placed well below the actual growth temperature of GaN on the substrates produces epitaxial grade GaN for the development of GaN on Si substrates. Occasionally, a few monolayers of Al have deposited over the substrate before AlN predeposition. These monolayers of Al serve as a barrier to the nitridation of the Si substrate.

Challenges of Si Substrates

The stress that arises during development is the major challenge in developing GaN on Si. Even with epilayer thicknesses of roughly 1 mm, cracks can form. Therefore, it is crucial to reduce the strain of producing GaN-based devices.

We must solve the high dislocation density and wafer cracking problems brought on by the lattice parameter and thermal expansion mismatch between GaN and Si to produce high-performance LED devices grown on Si substrates. Fortunately, by using AlN and AlGaN intermediary layers, we can manage the thermal stress in GaN films on silicon. To counterbalance the thermal tensile tension coming from the silicon substrate, the lower lattice parameter of AlN compels the GaN to be deposited in compression. We encourage threading dislocations to bend into the (0001)-plane and migrate laterally where they collide with dislocations of the opposite Burgers vector to minimize the density of threading dislocations using a silicon nitride interlayer.

GaN on Si Devices

The optoelectronic characteristics of III-Vs and other groups III nitrides have received the majority of research attention. Only electrical devices are currently created using GaN on Si since the optical elements of these films grown on Si are insufficient. Other areas of study include surface acoustic waves (SAW) devices made of group III nitrides and waveguide architectures, and GaN HEMTs are now the subject of extensive study.

The Future of GaN Integration

GaN is primarily used in three industries: LED, power, and RF. GaN sensors are the fourth application with a lot of potentials. Using GaN HEMT materials, researchers are looking at mercury detection, pH analysis, hydrogen sensing, DNA, and protein sensing, to name a few applications. Given that many sensors are silicon-based and the growing demand for numerous sensors on a single chip, often known as sensor fusion, it makes sense that GaN might offer up a variety of new applications for sensor innovation. It could not be too far off in the future to have a compact gadget with power, sensor, and optical capabilities.

Current Applications

Long employed in manufacturing RF and LED components, gallium nitride is now becoming more widely accepted in various power switching and conversion applications. GaN-based ICs may meet this requirement by delivering reliable operation at greater temperatures, saving space, and enhancing system performance and efficiency.

GaN RF components are used in phones and laptops to send and receive GSM and WiFi signals, and GaN is increasingly being used in the chargers and adaptors that power these devices. The mobile fast charging industry is the biggest market for power GaN. GaN power ICs can enable three times quicker charging in adaptors that are half as big and heavy as sluggish, silicon-based solutions. Additionally, the retail launch price of GaN for single-output chargers is around half that of earlier best-in-class silicon chargers and up to three times cheaper for multi-output chargers.

Servers in data centers are also using gallium nitride power semiconductors. Silicon's capacity to handle electricity effectively and efficiently encounters "physical material" barriers as data center traffic increases. Consequently, high-speed gallium nitride integrated circuits (ICs) replace the outdated, sluggish silicon chip. Significant efficiency gains are made possible by consolidating data center technology, a novel

HVDC design strategy, and the well-proven dependability of highly-integrated, mass-produced GaN power ICs. Global Si-to-GaN data center upgrades are predicted to cut energy loss by 30–40%, resulting in over 100 TWhr and 125 Mtons of CO2 emissions saved by 2030. Therefore, using GaN marks another step toward the data center industry's carbon "Net-Zero" aspirations.

Gallium nitride is becoming the preferred technology in the automotive sector for power conversion and battery charging in hybrid and electric cars. Inverters used in solar power installations and power conversion plans for motor drives and other industrial applications increasingly use GaN-based power products.

Several businesses are attempting to raise interest in GaN-based goods even though there aren't many devices that use GaN transistors. For instance, Panasonic has produced GaN-based transistors for use in power converters (with an efficiency of up to 99%) and as substitutes for transistors in motor topologies using its proprietary X-GaN technology. Their X-GaN transistors may replace MOSFETs and freewheel diodes, allowing energy conservation and reducing the circuit's overall size.

Due to their superior frequency characteristics, GaN transistors are also used in radio applications. Comtech PST Corp. has developed the model BPMC928109-1000, a GaN amplifier for speed cameras, air traffic control, and even military applications that require frequencies between 9.2 and 10GHz at 10kW of power.

Emerging Technological Applications Of GaN

Not only is GaN replacing ICs and many circuits we see in our day-to-day lives, but it is also impacting the newfound emerging technologies of our future. Notable ones include:

Autonomous Vehicle/Augmented Reality

Self-driving or autonomous automobiles are one fascinating application that looks into the future. If you look closely, you can see that the vehicle's "eyes" are a lidar (light distancing and range) system on top of the car. A 360-degree, three-dimensional image of the area around the vehicle is produced by the lidar device, which rapidly shoots a guided beam of light and records the time it takes for the beam to return and the direction in which it was shot. The resolution of the mapping or position of the items the lidar identifies increases with the speed at which the laser beam can be sent. GaN technology is crucial to the lidar system's operation because it allows the laser signal to be shot faster with similar silicon components.

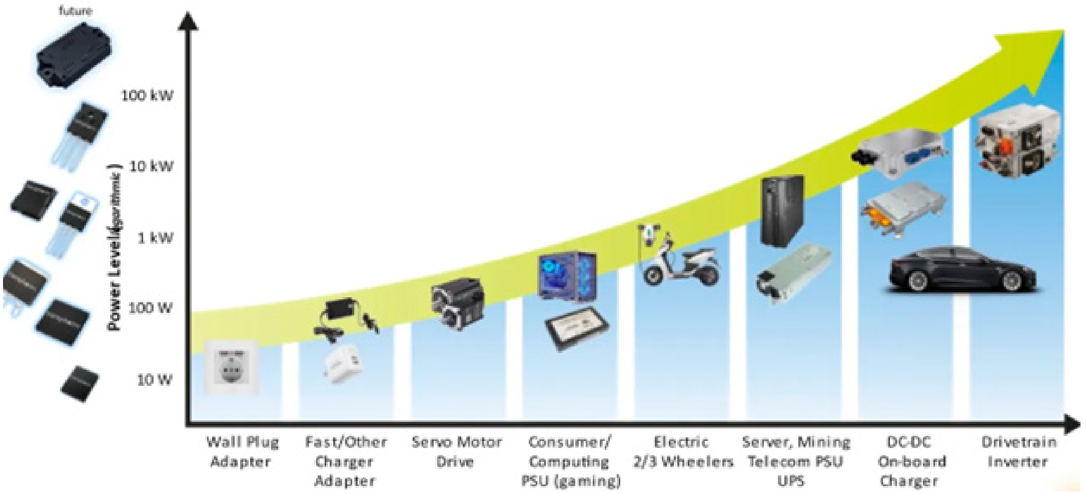
Augmented reality headsets that employ similar lidar technologies will show viewers three-dimensional visuals in real-time. Aside from the games we are now witnessing; augmented reality also allows soldiers to view the adversary in the distance as if they were right in front of them. A lidar drone is used to capture the picture from behind enemy lines. Regular people might use augmented reality headsets to view three-dimensional, real-time visuals of any location on Earth.

Space

Devices made of gallium nitride in space are a natural application area for GaN, given that gallium nitride is naturally radiation-tolerant. Unlike silicon, where specific production methods and packaging are required to protect semiconductors from radiation, GaN is reasonably resistant to these hazardous rays because of its inherent characteristics. GaN transistors are utilized in ion thrusters for converting solar panel electricity for satellites and lidar-based range applications. GaN devices are desirable for use in space applications due to their compact size, outstanding efficiency, and ability to survive in hostile environments.

Wireless Power

Another well-known use of GaN is the development of wireless power. We can cut the cord as wires are no longer required. Cell phones can already be wirelessly charged, and tablets, PCs, and even medical equipment on wheels are not far after. The car's center console will be used to charge phones wirelessly, eventually to charge the whole infotainment and navigation system. Ultimately, the transmitters and repeaters that will wirelessly power the lights, TV, and other home gadgets may be installed throughout the house. GaN transistors enable this innovative, quickly developing application, revolutionizing our lives.



Other exciting emerging applications of GaN include multi-junction photovoltaic cells, Data Center Servers, Power Electronics, Medical Technology, AI and Machine learning, IoT and 5G applications, Envelope Tracking, LNA & Communication Receivers, Millimeter Wave systems, Optoelectronics, and many more.

Challenges

GaN is much superior to silicon in terms of power efficiency, speed, and recovery qualities. GaN may appear to be a better option, but it won't completely replace silicon in all applications for some time.

Cost Of GaN Devices

GaN is a potential spintronics material when doped with an appropriate transition metal, such as manganese (magnetic semiconductors). GaN packaging choices are crucial because plastic-packaged high-power GaN enables designers to use traditional surface-mount production techniques and the corresponding manufacturing efficiencies. GaN on ceramic is still the go-to packaging material for electronics that must be hermetically sealed to function reliably under harsh environmental conditions. GaN devices that are ceramic-packaged can also handle significantly higher levels of power dissipation than the current plastic-packaged options.

Delivering components at a reasonable cost is the industry's most significant difficulty. The GaN manufacturing infrastructure will be put under a lot of stress as more commercial markets are penetrated, from packaging through device fabrication. The whole supply chain, starting with the availability of Silicon Carbide (SiC) substrates for the epitaxial growth of gallium nitride and ending with the commercial production of High Electron Mobility Transistors (HEMT), will need to adapt to the rising demand of the market.

Depletion-Type Transistors

Although GaN devices (such as LEDs) are often employed in optoelectronics, they are not frequently used in transistors for various reasons. GaN transistors are primarily depletion-type devices, which turn ON when the gate-source voltage is zero; it is one of the most significant obstacles since power circuits and logic depends on transistors that can be both ordinarily on and usually of.

The depletion nature of GaN transistors is the first obstacle that has to be solved; efficient power and logic circuits require transistors of both the normally-on and normally-off varieties. While normally-off GaN transistors are technically feasible, they either need extra layers that are difficult to remove or rely on standard silicon MOSFETs. GaN transistors are currently impracticable for use in CPUs and other microcontrollers due to their inability to be produced at the same scale as existing silicon transistors.

Possible Solutions

GaN is now the subject of more study to increase its effectiveness and accessibility. For example, Panasonic has patented a process for creating improved GaN transistors using an AlGaN layer. This implies that any breakthrough involving that particular transistor type will depend on Panasonic unless other businesses perform their research. These additional businesses are now working on their own improved GaN transistor manufacturing techniques. The results of these initiatives will determine how long GaN will remain competitive in the larger market.

To solve the depletion-type transistor problem, adding fluoride ions, using an MIS-type gate stack, combining GaN and Si devices, and using a P-type material on top of the AlGaN/GaN heterojunction are some current suggestions to make GaN devices that are OFF when the gate-source voltage is zero.

GaN transistors are still in their infancy despite the fact that work on GaN devices has been ongoing since the early 2000s. Over the next ten years, they will undoubtedly replace silicon transistors in power applications, but data processing applications are still a long way off.

GaN devices, however, might be used to replace silicon for improved power efficiency and work at much higher speeds, allowing the power of computers to keep growing, provided they can be made smaller (smaller than 100nm features).

Conclusion

Manufacturers of power supplies are constantly looking for methods to improve their goods' efficiency and power density. The advancements made to the silicon switches inside the power supply have contributed significantly to the benefits. With silicon devices being around for more than 70 years, GaN as a technology is still in its youth. Commercial availability of GaN products has just recently occurred. As demonstrated, applications that benefit from improved efficiency, switching speed, and compactness have already surfaced. Nevertheless, as the time for a new universal semiconductor almost strikes, it is up to GaN to fill that hole. As GaN technology advances, its end-use spreads, and its performance rises yearly; the future seems bright.

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