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Gallium Nitride (GaN) game changer for Aerospace and Military communications, radar, and electronic warfare (EW), applications

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November 7, 2019

International Defense Security & Technology (January 25, 2023) *Gallium Nitride (GaN) game changer for Aerospace and Military communications, radar, and electronic warfare (EW), applications*. Retrieved from <https://idstch.com/technology/electronics/gallium-nitride-gan-game-changer-for-aerospace-and-military-communications-radar-and-electronic-warfare-ew-applications/>.

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Integrated circuits and power devices utilized by the semiconductor industry for the production of advanced computers, consumer electronics, communication networks, and industrial and military systems have been almost exclusively based on silicon technology. The requirements of future electronics place a great emphasis on achieving new devices with greater power density and energy efficiency, especially in the power electronics arena. This emphasis poses an increasing challenge to come up with new design protocols, innovative packaging, and even new semiconductor materials, as it is widely believed that silicon technology has finally reached its fundamental physical limits. In addition to the devices' electrical requirements such as voltage and power ratings, the operational environments of power systems might encompass challenging conditions that include radiation, extreme temperature exposure, and wide-range thermal cycling, where conventional silicon-based systems are incapable of survival or efficient operation.

Power semiconductor devices are critical to the development of lightweight, highly efficient electronic systems needed for a wide variety of applications such as planetary exploration, deep space missions, terrestrial power grids, industrial machinery, and geothermal energy extraction.

The next generation of power electronics necessitates different types of semiconductor materials as today's dominant power semiconductor device material, silicon, is limited in terms of performance and efficiency at higher power levels and higher temperatures. WBG semiconductor devices, such as those based on GaN or silicon carbide (SiC), have emerged in the commercial market and have shown great potential to replace traditional silicon parts gradually in the high power arena.

Combining gallium (atomic number 31) and nitrogen (atomic number 7), gallium nitride (GaN) is a wide bandgap semiconductor material with a hard, hexagonal crystal structure. Bandgap is the energy needed to free an electron from its orbit around the nucleus and, at 3.4 eV, the bandgap of gallium nitride is over three times that of silicon, thus the designation 'wide' bandgap or WBG. As bandgap determines the electric field that a material can withstand, the wider bandgap of gallium nitride enables the development of semiconductors with very short or narrow depletion regions, leading to device structures with very high carrier density. With much smaller transistors and shorter current paths, ultra-low resistance and capacitance is achieved, enabling speeds that are up to 100x faster.

The benefits that GaN semiconductor devices offer over their silicon counterparts in power applications include greater efficiency at higher voltage, higher temperature operation, and higher frequency

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switching. GaN is a semiconductor material that can amplify high-power radiofrequency signals efficiently at microwave frequencies to enhance a system's range. Therefore it has become the technology of choice for high-RF power applications that require the transmission of signals over long distances such as EW, radar, base stations and satellite communications.

Military Applications

GaN devices were first developed for use in RF applications as they offer the best combination of power and gain at a given frequency, operation at higher voltages, and maximized efficiency. The high power density allows the construction of small devices with wide bandwidth leading to lower materials costs as well as reduced capacitance and losses, thereby rendering the devices attractive for use in high RF applications such as satellite communications, radars, and military warfare

GaN is a semiconductor material that can amplify high-power radio frequency signals efficiently at microwave frequencies to enhance a system's range. Therefore it has become the technology of choice for high-RF power applications that require the transmission of signals over long distances such as EW, radar, base stations and satellite communications. The adoption of GaN has been advancing significantly with several thousand devices been developed and implemented in applications such as radar, satellite communication, counter-IED jammers, 3G/4G base stations, WIMAX/LTE PAs, CATV modules, and general-purpose applications.

The simultaneous combination of high frequency, wide bandwidth, high power capabilities and high-temperature operation make GaN a natural fit for military applications. Gallium Nitride has become strategic material. Technology advances in utilizing GaN to develop violet, blue, green, and white light emitting diodes helped to improve the quality of the material. This paved the way for its utilisation in radar technology.

The technology has enabled military radars to operate at much higher frequencies and are used in jammers that allow fighter jets and other aircraft to fly undetected, said Colin Humphreys, a physics professor at Cambridge University. It is no surprise that United states want to stop China and Russia getting hold of gallium nitride technology, which can boost the power and sensitivity of weapons systems while reducing their cost as it requires less electricity.

Anti-IED

Military was the early user of GaN for Electronic Warfare applications, Anti-IED (improvised explosive devices) systems used GaN based Power Amplifiers to generate broadband microwave noise to disrupt and jam RF signals used to detonate the IEDs. Cree and Sumitomo were early suppliers of GaN on SiC devices for the IED jammers that were used in Iraq and Afghanistan.

US has identified this anti-IED capability as central to its future battle plans due to increasing threat of asymmetric warfare in future conflicts. The technology was also used in military communications; Nitronex shipped around a million GaN on Si devices for the Falcon multi-band tactical radio.

The older power amplifiers designs based on vacuum tubes, TWTs, klystrons, and older semiconductor technologies are being upgraded to Gallium Nitride (GaN) based solid state power amplifiers.

Tactical Radios

Gallium nitride (GaN), increasingly used in radar design, appears to now be migrating into tactical radios as well.

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In the communications domain, GaN can help reduce physical space and system complexity. An example of this is in wideband communications. Traditionally, tactical radios would have needed more than one transistor to cover each of the frequency bands used by the transceiver – in other words, a multiband radio would need multiple transistors.

Employing GaN enables a single transistor to perform multiband transmissions. Furthermore, a single wideband power amplifier using GaN components can perform the tasks of several narrowband amplifiers, each covering the radio's wavebands. These attributes are helping GaN to migrate into the tactical radio domain. For example, Harris is using GaN in its Falcon series of transceivers, and Persistent Systems has employed GaN in its MPU5 Wave Relay mobile ad hoc networking tactical radios.

This technology is particularly appropriate for the multiple-in/multiple-out (MIMO) approach that Persistent Systems employs on its MPU5 radio. This enables the equipment to overcome the restrictions that built-up environments usually impose on tactical radio users employing very high frequency (VHF) and ultra high frequency (UHF) wavebands for communications.

V/UHF signals rely on a line-of-sight range and can be disrupted or obscured by large objects such as walls or buildings. MIMO can divide a single signal into three, convert the signal to higher bandwidths such as L-band (1–2 gigahertz), and then transmit these signals to another MIMO radio where the disparate transmissions are then merged back into a single signal – but that process is reliant on the benefits provided by GaN.

Software Defined Radios

Broadband radios (portable, man-pack, mobile, and base station) demand ever wider operating bandwidths and are incorporating data and video capabilities in addition to two-way voice. The “network-centric” operations also demand broad bandwidth, “smart” and agile communications devices to stitch together all the information sources into a coherent network

Software-Defined Radio (SDR) architectures are playing an increasingly important role in emerging radio configurations with requirements for supporting multi-band and multi-standard operation. They will be reconfigurable by software which allows improved spectral efficiency and faster deployment of new standards.

Wide bandwidth and linearity requirements are critical to the ability of the SDR to adapt to multiple bands, modulation formats, and radio standards. For systems like the JTRS, power amplifiers need to operate over multi-decade bandwidth covering VHF, UHF, and L-bands, and need to be highly efficient and compact, especially when the amplifier is used in a handheld or mobile unit.

By using a single wideband PA instead of individual narrowband amplifiers for each band, significant cost savings are obtained through reduced component count. GaN HEMT devices with high breakdown voltage and high power density capability offer several advantages for broadband high power amplifiers. They can provide cost effective solutions that reduce system size and complexity while addressing the need for wideband power with efficiencies exceeding typical solutions used today.

Further advances in GaN technology and packaged Power ICs will provide future-proof solutions able to meet linearity requirements of more complex modulation waveforms envisioned with next generation multi-band, multi-standard portable and mobile SDRs.

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GaN is also attractive for LNA (low noise amplifiers) due to its excellent electrical robustness (high maximal field), which should simplify the system integration and improve overall performance

GaN's usage continues to expand in the military market. Its low sensitivity to ionizing radiation making it a suitable material for solar cell arrays for satellites. Military and space applications could also benefit as devices have shown stability in radiation environments.

AESA Radars

Next-generation radar systems are critical to providing situational awareness of the entire networked battlefield. Active electronically scanned array (AESA) radar systems operating in bands from UHF to X-band can produce very high-pulsed powers for surveillance applications or multiple simultaneous beams for shorter distance targeting and acquisition applications.

They contain a number of solid-state transmit/receive (T/R) modules that are combined at the antenna input. This array architecture enables simultaneous functions ranging from radar surveillance and fire control to jamming and advanced data link communications. Multifunction AESA versatility also enables dramatic improvements in target tracking, they allow for high-precision, multi-target tracking spanning both short- and long-range threats. The maturity, production ability and low risk of the GaN-based Radar Modular Assemblies are underpinning development of next generation radar system.

Raytheon's re-engineered Patriot radar prototype uses two key technologies – active electronically scanned array, which changes the way the radar searches the sky; and gallium nitride circuitry, which uses energy efficiently to amplify the radar's high-power radio frequencies. Raytheon has spent more than 15 years and \$200 million pioneering gallium nitride technology, and has built gallium nitride circuits for a number of products including jammers and other radars.

In June 2020, Raytheon Missiles & Defense provided a contract worth USD 2.3 billion to the U.S. Missile Defense Agency (MDA). The latter will deliver seven GaN-based Army Navy/Transportable Radar Surveillance (AN/TPY-2) units. It is a part of the company's Terminal High Altitude Area Defense (THAAD) system.

Enterprise Air Surveillance Radar (EASR)

The Navy has awarded Raytheon a \$92 million contract to develop a new for the Navy's new Ford-class carrier and big deck amphibious warships. The EASR will provide simultaneous anti-air and anti-surface warfare capabilities, along with electronic protection and air traffic control functionality, to the Gerald R. Ford-class carriers — starting with John F. Kennedy — and the planned LHA-8 amphibious warship.

The system replaces existing AN/SPS-48 and AN/SPS-49 air search radars and will take the form of an active electronically scanned array (AESA), also known as an active phased array radar. The system is based on Raytheon's gallium nitride (GaN) semiconductor technology. Radio frequency amplifiers made with GaN are five times more powerful than the ones in radars using traditional semiconductors, the company reported.

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By leveraging the advances already being made in the SPY-6 program, the new system “will enable the war fighters to conduct their mission with greater operational efficiency,” according to Dave Washburn, Raytheon enterprise air surveillance radar program director. “It will have the ability to execute the mission under modern threats in a challenged electronic environment,” Washburn said. The system has built-in “electronic protection capabilities ... to be able to counter electronic attacks. The threat space is continually evolving and radar needs to be able to perform in that evolving threat space. It has to cut through clutter, interference, jamming.”

GaN-Based AESAs Enable U.S. Navy’s Next-Generation Jammer

Raytheon engineers will incorporate the first demonstrator of this technology into the Next Generation Jammer (NGJ) program led by the Raytheon Space and Airborne Systems segment in McKinney, Texas. The NGJ is scheduled for lowrate initial production in 2018.

“We have only scratched the surface when it comes to harnessing the game changing power that gallium nitride technology can bring to military applications,” says Colin Whelan, vice president of advanced technology in Raytheon’s Integrated Defense Systems business unit.

U.S. Navy has commissioned a \$279.4-million contract to enhance the jamming features of the EA-18G Growler airframe to maintain air superiority in the modern battlespace when adversaries employ latest radar technologies. The contract called for standoff jamming technology that brings next-generation jamming assets to the U.S. Navy. Raytheon, which was awarded the contract, will implement a highly efficient AESA-based (actively electronically steered array) jamming system with powerful and wideband gallium-nitride (GaN) technology.

The array modules include electronics that use GaN high-power amplifiers (HPAs). Those amplifiers drive the power signals through the circulators and apertures to the array elements. The AESAs can therefore form high-energy RF beams with advanced signal capability that can be steered by a highly advanced and rapidly reprogrammable computer.

“Due to the nature of it being an AESA, you can form many beams or a super beam with a lot of energy. It is agile, so you can dart from one system to another system on the ground almost instantaneously,” says Andy Lowery, the NGJ chief engineer for Raytheon.

NASA studies space applications for GaN crystals

Two NASA teams are examining the use of gallium nitride, for potential applications in space. Among its many attributes, gallium nitride—GaN, for short—demonstrates less electrical resistance and thus loses only a small proportion of power as heat. The material can handle 10 times the electrical current of silicon, enabling smaller, faster, and more efficient devices. In addition, it’s tolerant to a wide range of temperatures, resistant to radiation, and as it turns out, adept at detecting energetic particles.

With their funding, engineer Jean-Marie Lauenstein and scientist Elizabeth MacDonald are investigating Gallium-Nitride High Electron Mobility Transistors, or GaN HEMTs, for use in studying how Earth’s magnetosphere couples to its ionosphere—a key question in the field of heliophysics, which among other things studies the forces that drive change in our space environment. Stanley Hunter and Georgia de Nolfo, meanwhile, are investigating the material’s use on a solid-state neutron detector that is relevant to both science and homeland security.

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Even though gallium-nitride is predicted to be resistant to many types of radiation damage encountered in space, neither NASA nor the U.S. military has established standards characterizing the performance of these transistor-enabled devices when exposed to the extreme radiation in space, said Lauenstein. When struck by galactic cosmic rays or other energetic particles, electronic equipment can experience catastrophic or transient single-event upsets. “We have standards for silicon,” Lauenstein said. “We don’t know if the methods for silicon transistors would apply to gallium-nitride transistors. With silicon, we can assess the threshold for failure.”

For de Nolfo and Hunter, gallium-nitride offers a potential solution for building a detector and imaging neutrons, which are short-lived and typically expire after about 15 minutes. Neutrons can be generated by energetic events in the Sun as well as cosmic ray interactions with Earth’s upper atmosphere. The neutrons generated by cosmic rays in the atmosphere can add to Earth’s radiation belt—a swath of radiation surrounding Earth that among other things can interfere with onboard satellite electronics—when they decay. Researchers have discovered GaN can form the basis of a highly sensitive neutron detector.

“The gallium-nitride crystal could be game-changing for us,” de Nolfo said. Under their concept, Hunter and de Nolfo would position a gallium-nitride crystal inside an instrument. As neutrons entered the crystal, they scatter off gallium and nitrogen atoms and, in the process, excite other atoms, which then produce a flash of light revealing the position of the neutron that initiated the reaction. Silicon photomultipliers attached to the crystal convert the flash of light into an electrical pulse to be analyzed by the sensor electronics.

“Gallium-nitride is reasonably well understood in the photo-electronics industry, but I think we’re pushing the envelope a little on this application,” Hunter said, adding that the beauty of the concept is that it would contain no moving parts, use little power, and operate in a vacuum. If it works, the instrument would benefit different space science disciplines and the military in detecting nuclear material, he added.

GaN technology

The second important advance was the substrates used for the GaN transistors. In electronics, a substrate, or wafer, forms the material onto which the transistors are built. Initially, GaN transistors used sapphire as a substrate, although this gave a less than optimal performance for transistors because of the latter’s poor thermal conductivity. A solution was then found by using silicon carbide. Although expensive at first, the increasing proliferation of GaN helped to reduce the cost, making GaN transistors economically viable. The material’s uptake in the civilian world was also instrumental in helping to reduce GaN’s costs.

GaN on silicon carbide (SiC) is being successfully applied in the military domain today, in applications such as broadband electronic warfare jammers and radar systems, while GaN on silicon (Si) has been successfully deployed in military communications.

System designers stand to benefit from GaN-on-SiC technology. McCann explains, “Thermally enabled and highly integrated laminate technology, when coupled with GaN-on-SiC, is allowing the system designer to now look to even greater levels of integration, notably extending primary radars to cover multiple bands in the same physical area and adding increased secondary radar functionality. Applications within the space market have also recently seen an increase in GaN-on-SiC feasibility work, notably in applications in which the efficiency of GaN is complemented by the ability to operate at ever-higher frequencies.”

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The Air Force Research Laboratory (AFRL) demonstrated the ability to grow and place the material on a flexible substrate, enabling the potential to power wearable devices or electronic devices that are not necessarily flat. "We are the first group ever to demonstrate a flexible radio frequency (RF) transistor device based on GaN that actually performs under strain and is flexible, which is quite powerful." According to AFRL scientists, GaN can be used in future communication systems by optimising just six atoms one ten-thousandth the width of a human hair.

In July 2019, Transphorm announced a new contract worth USD 18.5 million from the U.S. Department of Defense (DoD) Office of Naval Research (ONR). It includes a Base Program that is aimed at commercializing nitrogen polar GaN.

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Cite This Article

APA MLA Harvard Vancouver Chicago IEEE

International Defense Security & Technology (January 25, 2023) **Gallium Nitride (GaN) game changer for Aerospace and Military communications, radar, and electronic warfare (EW), applications.** Retrieved from <https://idstch.com/technology/electronics/gallium-nitride-gan-game-changer-for-aerospace-and-military-communications-radar-and-electronic-warfare-ew-applications/>.