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Wide Bandgap Semiconductors for Extreme Temperature and Radiation Environments

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Electrification and Energy Infrastructure Division
Nuclear Energy and Fuel Cycle Division

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ABBREVIATIONS

BJT	bipolar junction transistor
CMOS	complementary metal oxide semiconductor
COTS	commercial-off-the-shelf
Ga_2O_3	gallium oxide
GaN	gallium nitride
HEMT	high electron mobility transistor
I&C	instrumentation and control
IC	integrated circuit
JFET	junction-gate field-effect transistor
LED	light emitting diode
LEO	low Earth orbit
MOSFET	metal-oxide-semiconductor field-effect transistor
rad-hard	radiation-hardened
RF	radio frequency
RHBD	radiation-hardened by design
RHBP	radiation-hardened by process
SEB	single-event burnout
SEE	single-event effect
SEL	single-event latchup
SEL	single-event upset
Si	silicon
SiC	silicon carbide
SiO_2	silicon dioxide
TID	total ionizing dose
TMR	triple-modular redundancy
TRL	technology readiness level
VLSI	very large-scale integrated
WBG	wide bandgap

ABSTRACT

With their greater voltage breakdowns, higher current limitations, and faster switching speeds, wide bandgap semiconductors are increasing in market application over the traditionally dominant silicon devices. Silicon carbide semiconductors have been increasing the efficiency and reducing the footprint of modern power electronics, and the increased electron mobility of gallium nitride semiconductors have been increasing the switching frequencies of radio frequency circuits. In extreme temperature (>225°C) applications and high radiation environments such as low earth orbit, deep space, and terrestrial nuclear reactors, silicon-based semiconductors degrade rapidly. Wide bandgap semiconductors are poised to disrupt the market for sensing, instrumentation, and communication circuitry in these hazardous environments by increasing the lifetime, safety, and reliability. This report outlines the advantages of using wide bandgap semiconductor materials in extreme temperature and radiation environments.

1. INTRODUCTION

At present, implementation of in- or near-core nuclear reactor instrumentation and control systems requires placement of a detector at the desired measurement location within or near the core with long cabling run out of containment for interfacing. This cabling must cross spans of up to hundreds of meters to a remote room-temperature low-radiation location where the sensitive acquisition electronics may safely operate. The end result is not only multiple penetrations into reactor containment, but also electronically noisy signals complicating the already difficult task of reactor monitoring instrumentation and control (I&C).

Having radiation-hardened (rad-hard) electronics capable of operating within the high-radiation and high-temperature environment of an operating reactor core would allow for higher fidelity measurements through early signal pre-amplification, analog signal processing, and analog-to-digital conversion. The number of necessary penetration points into reactor containment could also be significantly reduced by using wireless communications or by sending multiple detector signals out over a single cable.

Rad-hard electronics technologies are also crucial for space applications, although that environment is fundamentally different. The environment inside a nuclear reactor is predominantly high-temperature with neutron and γ radiation, whereas the space environment can vary wildly in temperature extremes. In space, ionizing radiation primarily takes the form of energetic charged particles and x-ray radiation. Additionally, whereas the flux in particles per second are overall much lower in space, the inability to perform maintenance on the system means that the equipment must perform reliably over much longer time periods.

Fission reactors have an immediate need for rad-hard electronics, and in the near future, fusion reactors will require the same. Fusion reactors will operate at much higher temperatures than fission reactors, further complicating the issue of electronic survivability.

The roadmap (see Fig. 1) for rad-hard in reactor environments has three possible paths: use of *space-rated* electronics, use of commercial-off-the-shelf (COTS) *component-wise* design solutions, or development of *fully custom* electronics from the transistor level. *Space-rated* components have a high technology readiness level (TRL) and are commercially available, but they are typically irradiated to 0.3–1 Mrad (Si) and rarely have any established neutron limits. Because of their availability, design time and associated costs are low. However, the device behavior under irradiation, which is particularly critical for analog circuitry, is often omitted from their data sheets. Performing the necessary irradiation and associated verification procedures will result in significant increases in system development costs. *Component-wise* system development entails using commercially available components with high intrinsic radiation resistance, such as junction-gate field-effect transistors (JFETs) that have withstood >100 Mrad (Si), to develop a lower cost solution with a radiation tolerance well beyond that available in commercial offerings. The design time required for these systems and the associated costs will be low. However, the systems will require multiple irradiation evaluations at the device and circuit levels. This may result in multiple design iterations to locate suitable components or to compensate for radiation effects. The *fully custom* rad-hard electronics pathway begins with designing radiation-resistant electronic components, integrated circuits (ICs) (small scale to very large-scale integrated (VLSI) circuits), or complete systems-on-chips (SoCs). This route includes both radiation-hardened by design (RHBD) and radiation-hardened by process (RHBP) techniques. RHBD typically incorporates low-level device layout, placement, and routing, and it may incorporate redundancy and voting schemes such as triple-modular redundancy (TMR) or error correction codes to reduce soft (recoverable) errors caused by large transient radiation. RHBP focuses on device construction and materials—such as small feature size complementary metal oxide semiconductor (CMOS) or wide bandgap (WBG) materials—to design more radiation-resistant semiconductor devices. This pathway is has the highest costs for design time and prototyping, because it starts from a foundational TRL. However, this design approach has the potential to produce circuits and systems with very high radiation resistance at a low fabrication cost for reasonable volume production.

This report briefly discusses the background of radiation damage to semiconductors and the RHBP technique of using WBG semiconductors to increase radiation resistivity over silicon (Si) electronics. Semiconductors developed using three materials of interest—silicon carbide (SiC), gallium nitride (GaN), and gallium oxide (Ga_2O_3)—are discussed, and their performance and associated radiation effects are compared to Si-based transistors.

2. RADIATION DEGRADATION MECHANISMS IN SEMICONDUCTORS

Semiconductors are the limiting factor in high-temperature, and high-radiation–resistant electronics. Silicon-based semiconductors have thermal limits of approximately 225°C, and the various topologies of transistors have radiation limits as described in Tables 1 and 2. To understand the limiting factors in semiconductors, one must understand how they are affected by radiation. In this section, these effects are briefly discussed. More detailed analysis is provided in the report by Reed et al. [1] or Messenger [2].

Table 1. Neutron displacement damage on Si device technologies [1]

Technology	Max fluence (n/cm^2)	Displacement effects
Diodes	10^{13} – 10^{15}	Increased leakage currents; increased forward voltage threshold
LEDs	10^{12} – 10^{14}	Reduced light intensity
BJTs	10^{13}	Current gain degradation
JFETs	10^{14}	Increased channel resistivity; decreased carrier mobilities
MOSFETs	10^{15}	Increased channel resistivity; decreased carrier mobilities
CMOS	10^{15}	Increased channel resistivity; decreased carrier mobilities

Low Earth orbit (LEO) environments and reactor environments are the preponderate applications requiring rad-hard electronics. However, the radiological profiles of these two environments are quite different. In LEO and other space applications, the dominate forms of radiation are heavy atomic nuclei, protons, alpha and beta particles, and high-energy photons from intensive solar events such as supernovas or solar flairs.

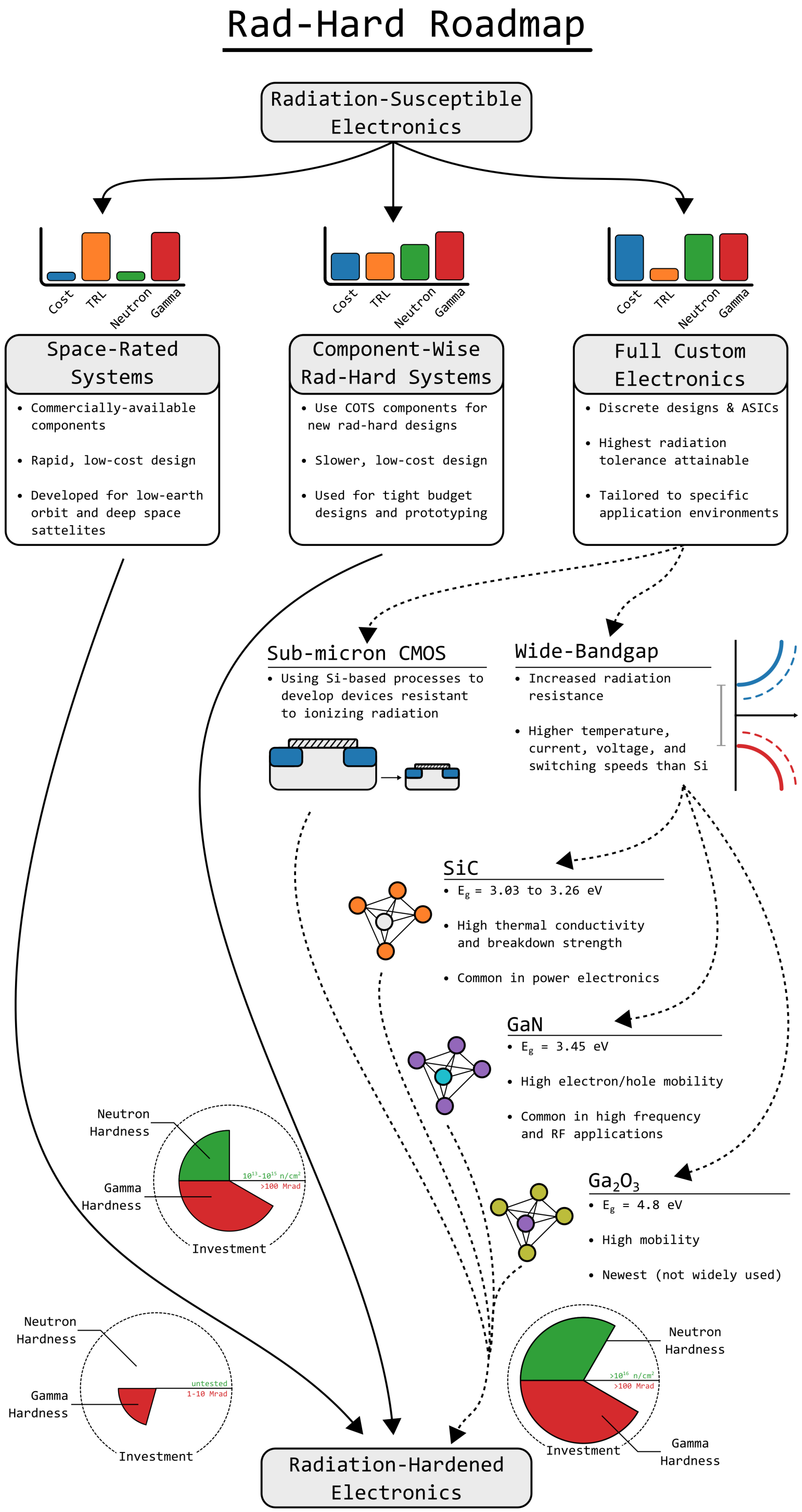

Figure 1. Pathways to develop radiation-hardened electronic systems.

Table 2. Gamma TID damage on Si device technologies [1]

Technology	TID (Gy)	TID Effects
Photodiodes	10^4 – 10^6	Increased photocurrents
LEDs	10^5 – 10^6	0.25 dB attenuation
BJTs	10^3 – 10^5	Current gain degradation and increased leakage currents
JFETs	$>10^6$	Minimal observable effects
MOSFETs	10^4	Increasing threshold voltage and leakage currents
CMOS	10^6	Variations in threshold voltage and leakage currents

Although the radiative dose rates in these applications are large, the overall absorbed dose or total ionizing dose (TID) remains low compared to those seen in reactor applications. Few neutron interactions occur in these communications and in exploratory research applications except in the presence of reactors used for deep space missions. Nuclear reactor applications are neutron intensive, and they generate secondary ionizing radiation as a result of the decay byproducts of nuclear fuels. In general, the radiation effects on electronics and semiconducting devices are categorized by the neutron fluence, TID, and ionizing dose rate.

Neutron kinematics are semiconductors that are dependent on the neutron energy. Because neutrons are of less concern to space applications except for those involving nuclear thermal propulsion, the primary neutron energy levels associated with electronics applications are those of terrestrial nuclear environments. Thermal (0.025 MeV) and fast (1–20 MeV) neutrons are the predominate neutrons associated with the most common fission reactors. Neutron fluence is defined as the integrated number of neutrons of energy E per cm^2 (n/cm^2) penetrating a medium for a given time interval, and flux is defined as the number of neutrons of energy E per cross-sectional area per unit time (n/cm^2). These are the principle quantities used to discuss these effects.

Because of their high energies, fast neutrons displace atoms in the lattice structure during collisions [2]. If the incident neutron imparts sufficient energy to the ejected atom, then it will continue to collide with surrounding atoms, thus cascading the damages. The displaced atoms may return to their original lattice location, or they may combine with semiconducting dopants or impurities to create stable defects, leaving behind voids in the lattice structure. Thermal annealing accelerates the atomic motion, which can lead to the displaced atom filling a void or creating stable defects. Both voids or defect complexes are effective centers for recombination or trapping charge carriers, and they reduce the minority carrier lifetime of the semiconducting materials, often resulting in decreases in transconductance and common emitter current gains. Voids and stable defects increase the resistivity of semiconductor material.

Each deflected neutron will continue to collide with atoms in the material lattice structure until it either escapes or thermalizes. When the neutron has reached a sufficiently low energy state, it may be absorbed by an atom, thus creating an unstable isotope. To reach stability, the isotope will decay through alpha or beta emissions to reach stability. Gamma rays will be emitted if the isotope nucleus enters an excited state through the decay process or neutron interactions.

Ionization through incident beta particles occurs through scattering, excitation, bremsstrahlung, and positron annihilation [3]. Incident high-energy (gamma) photons interact with atoms via the photoelectric effect, the Compton effect, and pair creation. Broadly, the effects of ionizing radiation on semiconductors and electronics are caused by the TID and the dose rate. Long-term effects related to charge trapping, conductivity increases, and the shredding of covalent bonds are attributed to TID effects, whereas short-term effects generate increased photocurrents, propagation delays, and single-event effects (SEEs).

Because of their large bandgap and low charge carrier (free electron and hole) mobilities, electrical insulators (materials with resistivity greater than $10^5\ \Omega \cdot m$) are susceptible to trapped charges [4]. As these trapped charges accumulate, electric fields are formed which can cause dielectric breakdowns, generate currents, or bias field effect transistors. Silicon dioxide–insulating surface layers (passivation layers) expand as a result of these trapped charges, reducing minority carrier lifetimes and current gain of field effect transistors and bipolar junction transistors (BJTs) [2]. These surface layers not often rigorously controlled in the manufacturing of common (non-rad-hard) COTSs components, so there is a high degree of variance in the radiation hardness of rad-soft components.

An erroneous random bit flip is a type of SEE known as a single-event upset (SEL) or single-event latchup (SEL) [5, 6]. These upsets occur under a large influx of ionizing radiation that rapidly produces charge on a digital logic gate. As smaller feature size integrated circuit processes have been implemented, SEEs vulnerability has increased as a result of the increased semiconductor density in VLSI circuits as described by Moore's law. Both triple modular redundancy (a redundant voting scheme created by three identical circuits) and error correction codes are common techniques to mitigate SEEs.

3. WIDE BANDGAP SEMICONDUCTORS

WBG-based semiconductors have intrinsic advantages over Si for power and high-frequency electronics. Table 3 compares various semiconductor properties the semiconductor materials discussed herein. The three WBG materials shown have greater breakdown fields than Si, leading to higher voltage limits and doping concentrations. Of these materials, GaN has the highest electron mobility, making it the most suitable semiconductor material choice for applications requiring fast switching (e.g., communications). For high current applications, SiC is a natural choice, as it has the largest thermal conductivity, leading to higher power density operation. With the highest breakdown field, Ga_2O_3 is enticing for use in high-voltage applications with low current requirements and for cases in which long switching times are acceptable. The maximum operational temperature of each WBG material depends on the device processing technology and not the heterostructure material stability [7]. The temperatures provided in Table 3 are very conservative [8].

Table 3. Semiconductor characteristics of Si, SiC, GaN, and Ga_2O_3 [9, 7, 10]

Property	Si	SiC	GaN	Ga_2O_3
Bandgap energy (eV)	1.12	3.25	3.4	4.5–4.9
Dielectric constant	11.8	9.7	9	10
Breakdown field (MV/cm)	0.3	2.5	3.3	8
Thermal conductivity (W/cm·K)	1.5	4.9	2.3	0.25
Electron mobility (cm^2/V·s)	1,500	1,000	1,250	300
Max. operating temperature (°C)	225	500	600	500

3.1 SILICON CARBIDE SEMICONDUCTORS

SiC wide bandgap-based semiconductor devices are increasingly common in modern power applications involving one or more of the following: high voltage, high power, high frequency, and high temperatures. Initially, the semiconductor processing of SiC was prohibitively expensive compared to bulk silicon CMOS process fabrication. The cost has significantly reduced in recent years, fueling proliferation in multiple power markets, including the cost-sensitive automotive electronics market associated with electric vehicles, where battery chargers, power conditioning (dc-dc, ac-dc, and dc-ac converters), and traction drive systems are commonplace.

Several types of common electronic devices are now based on SiC, including metal-oxide-semiconductor field-effect transistors (MOSFETs), bipolar transistors, and JFETs. SiC fabrication processes offering MOSFETs devices are typically limited to n-type only because there is no complementary p-type device as in CMOS. There has been very limited availability of true CMOS-type fabrication technology based on SiC, but the fabricated p-type devices are impeded by SiC's much-reduced hole mobility compared to that of silicon.

For harsh environment applications, a significant amount of work has been performed for SiC-based circuits operating at elevated temperatures. Examples include data converters in SiC CMOS at 400°C [11], radio circuits in SiC bipolar technology at 500°C [12], voltage and current references in SiC CMOS at 540°C [13], and SiC JFET technology operated at 500°C [10].

Neutron irradiation studies of SiC transistors have been the subject of recent research interest, especially pertaining to commercial power devices. SiC MOSFETs power devices have been the most extensively studied [14, 15]. Failures within 10^5–10^9 n/cm^2 for these devices are common, and the mechanisms causing these failures on commercial devices are being investigated [16, 17]. Single-event burnouts (SEBs) are the dominant source of failure, and they occur from increased currents as a result of recoil ion trails [18]. In SiC JFETs, 10^{14}–10^{16} n/cm^2 fluences have been reported with decreasing free carrier concentrations, increasing drain-to-source resistance, and variations in threshold (pinch off) voltage [19, 20, 21].

As in neutron studies, ionizing irradiation research of SiC transistors has been more widely investigated for power devices. As with Si MOSFETs, charge trapping occurs in the silicon dioxide (SiO_2) gate insulation and surface regions of MOSFETs, resulting in illicit biasing of the device, increasing surface current densities, and voltage breakdowns of the devices. Gamma irradiations of up to 100 Mrad (SiO_2) have been reported in SiC MOSFETs, demonstrating decreased hole mobility, decreased threshold voltages, and increased charge trap densities [22, 23, 24]. SiC JFETs have been extensively studied since the early 1990s and have been shown to demonstrate the radiation-hardness associated with their Si counterparts [20]. At TIDs of 100 Mrad (Si), these devices are inherently tolerant to ionizing radiation as a result of the lack of a gate insulator, and they commonly exhibit only minor variations in their pinch-off voltage and transconductance [25, 26, 27]. However, the fabrication process of these transistors varies greatly, as with any commercial transistor, and those devices that feature extensive SiO_2 or other passivation layers will be more sensitive to gamma radiation and other ionizing radiation. Fortunately, the NASA Glenn Research Center has been investigating SiC JFET devices for Venus exploration and has consistently shown >7 Mrad (Si) ionizing radiation tolerance for their SiC integrated circuits [10, 28, 29].

3.2 GALLIUM NITRIDE SEMICONDUCTORS

GaN-based high electron mobility transistors (HEMTs) and light emitting diodes (LEDs) are growing in popularity. The LEDs produce a blue light, but by exciting a phosphor in the yellow wavelengths, they have been effectively used to create white light with efficiency an order of magnitude better than that of incandescent lights. GaN-based HEMTs exhibit higher electron mobility and bandwidth than Si-based transistors, making them attractive for high-frequency and radio frequency (RF) applications. Like SiC-based transistors, the voltage breakdown of GaN transistors is greater than that of Si, allowing for increased semiconductor doping.

As expected, neutron irradiation produces greater semiconductor damage than photons in GaN. Semiconductor resistance increases as a result of displacements as a function of fast neutron fluence [30] in GaN semiconductors. These HEMTs have been shown to withstand 10^{15}–10^{16} n/cm^2 neutron fluence that induces decreases in mobility, increases of charge traps, increases of carrier removal, and the introduction of nitrogen vacancies in the lattice structure from displacements [31]. Fermi-level pinning occurs for fast neutrons, creating deep acceptor defects in n-type materials and a deep donor in p-type materials [32].

GaN HEMTs have been shown to be less susceptible to large TID up to 600 Mrad [30] compared to Si devices. However, variations in the dose limits and damage types can be attributed to different device structures, including the SiO_2 or other insulating surface layers. The types of damages that are reported consistently include an increase of drain saturation current [33, 34], an increase of electron mobility at low dose by 7–8% [35, 36], negative threshold shifts, decreases in gm, and increases of reverse breakdown voltages [37].

4. CONCLUSIONS

There is a clear need for new electronics technologies that can withstand the extreme radiation and temperature environments associated with terrestrial reactor monitoring and control. Clean carbon-neutral power generation has significantly increased commercial interest and investment in new advanced terrestrial reactor technologies. These growing developments will only fuel a greater need for these new electronics technologies, as advanced reactors are built and move towards commissioning. This report and the report by Reed et al. [1] present a roadmap outlining approaches to achieve more robust rad-hard sensors and electronics suitable for use in these extreme temperatures and high-radiation environments. Placing sensor-supporting electronics closer to the sensing elements will increase the signal fidelity by reducing the noise and interference inherent in lengthy cabling. New harsh environment electronics technologies will enable more prolific use of sensors in or near the reactor core, resulting in improved efficiency and safety.

Si JFET-based electronics have demonstrated tolerance to ionizing radiation beyond 100 Mrad TID and 10^{14} n/cm^2 neutron fluence. However, Si transistors typically have thermal limitations between 150–225°C. Transistors fabricated using WBG materials have demonstrated operation beyond 500°C and have increased the neutron fluence limits by two orders of magnitude beyond that of Si while remaining tolerant to the rigorous 100 Mrad TID magnitude.

WBG-based transistors continue to grow in popularity for commercial power electronics and RF applications because of their higher breakdown voltages and better thermal conductivity. Mature, competitively priced SiC devices are commonly used in battery chargers and power conditioning circuitry, but the lack of the complementary pair of these devices is a obstacle to development of fast, efficient ICs. Researchers at the NASA Glenn Research Center have developed a mature SiC JFET IC process with standard cells and extensive design experience, making these devices enticing for rad-hard harsh environment applications. GaN-based transistors are less mature than SiC transistors, but they have demonstrated excellent radiation resistance. In RF applications, GaN is quickly becoming the preferred semiconductor material, which aligns well with these devices for application to rad-hard communications. Ga_2O_3 is an emerging WBG semiconductor material that has not yet been extensively explored in high temperature, rad-hard, or benign environments. Future research may show this new material as a strong candidate for the extreme harsh environments associated with in- or near-reactor core applications.

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