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Ultra-Wide Bandgap Semiconductors Workshop III

by R Kaplar, H Zhao, K Goretta, N Johnson, M Hollis, T Ivanov,
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K A Jones, Editor

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14. ABSTRACT With their very large energy gaps and associated larger critical electric fields and greater bond strengths, ultra-wide bandgap (UWBG) semiconductors have the potential to handle more power and operate further into the deep UV, better at higher temperatures, and better in corrosive environments. However, various challenges, often unique to the individual UWBG semiconductor, have to be overcome for that semiconductor to reach its potential. For example, beta-phase gallium oxide (β -Ga ₂ O ₃) has a small thermal conductivity, aluminum gallium nitride (AlGaN) is lattice mismatched with the substrate it grows on, and diamond has only deep donors and acceptors. The recent progress made on these and other challenges are discussed along with the dielectric, magnetic, and thermal materials that will also be required for these semiconductors to reach their full potential.					
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Executive Summary

Author: K Goretta

Ultra-wide bandgap (UWBG) semiconductors can be defined as having a bandgap greater than 4 eV. They offer unique properties in optoelectronics and the promise of high speed and high power in a variety of applications, including those with high operating temperatures. In recent years, many conferences and workshops have focused on the status and prospects of these materials. A workshop on UWBG semiconductors was held on 14–16 May 2019 at the US Army Combat Capabilities Development Command Army Research Laboratory, Adelphi, Maryland. Inputs from that workshop form the foundation of this report. Recent advances are added to those presented at the workshop.

The report consists of six sections, organized by both class of semiconductor and prospective applications. Following an introduction, Section 2 covers beta-phase gallium oxide alloys (β -Ga₂O₃). Section 3 covers aluminum gallium nitride (AlGaIn) alloys and a number of its applications. Section 4 covers diamond and related materials and devices. Section 5 covers materials in support of various technologies: thermal, magnetic, and dielectric materials. Section 6 focuses on specific applications in optoelectronics, high-power electronics, and high-operating-temperature sensors.

Gallium Oxide and its Alloys

Of the various polymorphs of Ga₂O₃, β -Ga₂O₃, with its bandgap of 4.5–4.9 eV, receives the most attention in research and development. (Ga,In)₂O₃ alloys with smaller bandgaps and (Ga,Al)₂O₃ with larger bandgaps are also being developed. Much of the interest in Ga₂O₃ is due to the availability of large-area, native substrates. These substrates can be grown by melt-growth techniques that include floating zone, Czochralski, Bridgman, and edge-defined film-fed growth.

Various deposition techniques now yield high-quality, epitaxial Ga₂O₃ films. These techniques include pulsed laser deposition, metal-organic chemical vapor deposition (MOCVD), low-pressure chemical vapor deposition (CVD), molecular beam epitaxy (MBE), hydride vapor-phase epitaxy, and metal-oxide catalyzed epitaxy. Silicon (Si)-doped films grown by MOCVD have achieved mobilities exceeding 180 cm²/Vs at room temperature, and unintentionally doped films have shown room-temperature mobilities greater than 190 cm²/Vs.

Controlled doping is, of course, essential for use. Ga₂O₃ is now n-doped with elements such as Si, tin, and germanium. Commercially viable p-doping has yet to be achieved. Doping must be coupled with a thorough understanding of defects.

Defects and their distributions in Ga_2O_3 are complex. Present are three types of oxygen (O) vacancies, two types of gallium (Ga) vacancies, and several types of defect complexes. O vacancies, V_{O} , appear to be a deep n-type donor. Ga vacancies, V_{Ga} , and their complexes are energetically favorable. Background elemental impurities, such as Si and hydrogen, can significantly impact conductivity and compensation can occur. Experimental techniques reveal universal defects at $E_{\text{C}} = 0.8 \text{ eV}$ and $E_{\text{C}} = 4.4 \text{ eV}$, as well as others that depend on factors such as the growth technique and doping. Further studies of defects in Ga_2O_3 are much needed.

The most common alloys of Ga_2O_3 being studied are narrower-bandgap $(\text{Ga},\text{In})_2\text{O}_3$ and wider-bandgap $(\text{Ga},\text{Al})_2\text{O}_3$. The crystal structures formed depend on the alloy composition. High-aluminum (Al)-content $(\text{Ga},\text{Al})_2\text{O}_3$, which will facilitate higher-power application, remains to be demonstrated experimentally.

High-power operation generates heat, and the thermal conductivity of any material is an important factor in determining its use. The thermal conductivity of Ga_2O_3 is in the range of $0.1\text{--}0.3 \text{ W/cm}\cdot\text{K}$ at room temperature, which is lower than that of other UWBG semiconductors. Ongoing research of Ga_2O_3 and its alloys includes thermal transport and engineering packages for management of heat.

Ga_2O_3 devices have already achieved impressive performance. High breakdown-field strengths in the range of $6\text{--}8 \text{ MV/cm}$ have led to exceptional unipolar power devices. Recent advances, such as modulation doping, formation of high-mobility 2-D electron gases in $(\text{Ga},\text{Al})_2\text{O}_3/\text{Ga}_2\text{O}_3$ heterostructures, and fabrication of fin arrays, can expand the range of useful devices. In addition to power devices, optoelectronic devices such as solar-blind photodetectors are being pursued.

AlGaN and Related Nitride Materials and Devices

AlGaN alloys encompass a range of composition and, hence, bandgap. Beginning with gallium nitride (GaN) and 3.4 eV , they extend to approximately 6.0 eV . From an optoelectronics perspective, these energies equate to light emission at wavelengths of $215\text{--}365 \text{ nm}$. Taking the best properties among the alloys, breakdown fields can potentially be greater than 10 MV/cm , electron mobilities can reach $1000 \text{ cm}^2/\text{Vs}$, and saturation velocities can potentially exceed 10^7 cm/s . As with Ga_2O_3 , n-doping can be achieved readily.

The review begins with a discussion of the status of modeling of GaN alloys. Although much has been published, much remains to be done, especially with respect to defects. A recent advancement of note is treating the alloys' structural and electronic properties by statistical methods, rather than relying on averaging methods. Experiments are needed to measure material properties accurately and, one hopes, validate theoretical models.

Many strides forward have been made in epitaxial growth of UWBG nitride films. For example, growth of transition metal nitride heterostructures by MBE is now under investigation. Discussion focuses on challenges in synthesizing these alloys. A number of competing phases often exist for a nitride compound. A slight change in stoichiometry can yield a different phase. Precise control of growth parameters is needed to produce high-quality films.

Because of the multitude of possible phases, it can be challenging to grow high-quality heterostructures. Beneficial properties of these heterostructures suitable for devices include high spontaneous polarization and piezoelectric response, dry etch resistance, and, for a few compositions, superconductivity. Electrical, mechanical, and processing advantages can all be exploited to enable new devices. As an example, acoustoelectric devices based on scandium aluminum nitride leverage electronic and acoustic wave transport in a thin-film, lateral design.

The status of growing AlGaN films by MOCVD is discussed. AlGaN power transistors grown by MOCVD offer many significant advantages over those based on Si, gallium arsenide, silicon carbide (SiC), and GaN, including higher unipolar figures of merit. As an example, quasi-vertical $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ PiN diodes have demonstrated greater than 3-kV reverse voltages with less than 1-mA leakage current. Challenges remaining for AlGaN transistors include achieving higher blocking voltages, lower reverse leakage currents, and fully vertical device geometries.

Included in the AlGaN discussion is growth of aluminum nitride (AlN) single-crystal substrates for optoelectronic and electronic applications. High-quality, UV-C transparent, 2-inch-diameter wafers are now used in production. Their cost is comparable to that of semi-insulating SiC substrates. High-volume production may reduce the cost by an order of magnitude. AlN substrates have much lower threading-dislocation densities than do AlN templates grown on sapphire, which enables production of devices with superior properties.

High-quality bulk AlN substrates now enable a wide range of new device applications. AlN can be suitable for use at high temperatures and in harsh environments. UV-C LEDs with superior performance are commercial products. It is noted the surface disinfection market grew dramatically with the SARS-CoV-2 (COVID-19) pandemic. Demand for UV-C LEDs, especially in the 260- to 270-nm wavelength range, increased markedly. A UV-C laser diode, which operates at 271 nm, was produced recently. High-performance and/or low-cost UV-C solid-state detectors, high-power RF electronics, and high-power switches are all being developed.

Because of their range of UWBG, optical transparency from 0.21 to 13.6 μm , excellent nonlinear optical properties, high thermal conductivity, and high radiation tolerance, AlGaIn alloys are uniquely suited as a platform for photonic integrated circuits (PICs) operating in the UV and visible. Through nonlinear frequency generation processes, for example, AlGaIn micro-ring resonators can operate from the UV to the IR. Because indium aluminum gallium nitride semiconductors of various compositions are used for both optoelectronic and electronic devices, it may be possible to achieve compact, deployable PIC systems for positioning, navigation, and timing that are based on trapped atomic ions having electronic transitions in the UV/visible range.

Diamond

Diamond is unique among semiconductors in offering unsurpassed thermal conductivity, a high breakdown field owing to its large bandgap of 5.5 eV, and good carrier mobilities and saturation velocities for both electrons and holes. Diamond electronics have great promise for power switching, RF amplification, and many other applications.

Several types of metal-insulator-semiconductor field-effect transistors (MISFETs) have been recently demonstrated. Various surface treatments and insulators on diamond channels have been applied. Channel current densities as high as 700 mA/mm and maximum unity-current-gain frequencies (f_{r}) and oscillation frequencies (f_{max}) as high as 75 and 120 GHz, respectively, have been achieved. Ohmic contact resistances as low as 0.49 $\Omega\text{-mm}$ for contacts exhibiting excellent adhesion have been reported. Recent advances in surface passivation methods have achieved stability in MISFET channel current density in tests that exceeded 200 days. Wafer-bonding and grafting techniques now enable fabrication of high-performance heterojunction bipolar transistors.

Diamond diodes for power switching and particle detection continue to progress. Blocking fields and voltages of 3.9 MV/cm and 1840 V, respectively, have been demonstrated, and current densities as high as 2700 A/cm² at room temperature have been shown. Diamond diodes as neutron detectors now exhibit high efficiency and negligible radiation damage.

Commercial semiconductor-based electronics require availability of relatively large, high-quality substrates. Wafer size is a long-standing challenge for diamond. Recent progress reveals potential pathways toward larger-area diamond substrates. A team at the University of Augsburg in Germany reported, in 2017, plasma-CVD growth of a 92-mm-diameter, 1.6-mm-thick single-crystal layer of diamond on a Si substrate. This de-facto existence proof that large diamond wafers can be

manufactured by an inexpensive technique such as plasma-CVD is an inspiration to the field.

The diamond section states it will likely take more than a decade to develop many applications to points where the potential payoffs are manifested in wide-scale commercial application. It further states the large, often unique payoffs merit increasing the current investment in diamond growth and devices. Suggested areas of underpinning investment are thought to include the following:

- 1) Large (2 and 4 inch) and ultimately foundry-sized diamond substrates are needed. They will speed progress in use of Si-grade lithography, deposition, and etching tools for tight control of transistor properties. Polishing methods to produce low-defect monolayer smoothness continue to be investigated.
- 2) Support should continue for refinement of epitaxial-growth technologies for high-quality, low-defect diamond films, and growth of related materials, such as cubic boron nitride (c-BN) (close lattice match) on diamond and vice versa.
- 3) Diamond transistors and diodes, including complementary transistor designs, continue to offer immense promise. Two types of complementary transistors are most probable: p- and n-channel diamond MISFETs and p- and n-channel c-BN/diamond modulation-doped field-effect transistors or high-electron-mobility transistors.
- 4) Still needed are theoretical and experimental studies to define, understand, and control the unique features of carrier transport in diamond and to optimize transport in real devices.

Supporting Technologies

UWBG semiconductors must be coupled with various other materials to produce useful systems. Perhaps most essential are improved thermal materials and interface designs, because of the comparatively high power densities expected of UWBGs. A co-design approach will be needed. In addition to materials and design, experimental and modeling techniques must exhibit fidelity on microscopic scales. Through a combination of in-situ Raman thermometry, thermos-reflectance thermal imaging, and IR thermography, channel temperature profiles can be measured. Understanding self-heating of UWBG devices requires the knowledge of heat generation and the operating thermal-transport mechanisms. Heat-generation profiles can be inferred from coupled electro-thermal simulations. Phonon transport across the layers of UWBG devices can be characterized by optical pump-probe methods, such as frequency-domain thermo-reflectance. It has

been observed, for example, thermal resistances of β -Ga₂O₃/4H-SiC composite substrates are highly dependent on the β -Ga₂O₃ crystalline quality and interfacial thermal boundary resistance.

Developing more accurate techniques for measuring thermal conductance, particularly across interfaces, is an ongoing challenge. A new technique, steady-state thermo-reflectance (SSTR), has been developed for measuring thermal conductivity of bulk substrates and thermal conductance across bulk interfaces. Unlike transient thermo-reflectance, SSTR can characterize thick layers—from 2 to 500 μ m thick, depending on spot size—and it can measure thermal conductivities over 3 orders of magnitude.

Strategies for dealing with heating issues in high-electron-mobility transistors include flip-chip approaches and applying cooling from the top side by jet-impingement of a dielectric fluid. Double-sided jet impingement cooling is also being explored. As a measure of progress, results to date have come far in achieving the 2025 automotive power-density goals for the US Department of Energy (DOE) Vehicle Technologies.

The high frequencies expected of active UWBG power devices will require development of new passive power electronic components. Advanced soft magnetic materials are required to enable UWBG semiconductors to achieve their promised high power densities and switching frequencies. These materials will lead to immense reductions in the size and weight of inductors, transformers, and other electric machinery. Desired properties of suitable soft magnetic materials include high saturation magnetizations, which enable high power density; low coercivities, which enable low hysteretic losses; high resistivities, which enable low eddy-current losses; and low magnetostriction, which reduces the mechanical strain. For applications at the kilowatt scale and above, additional desired properties include high-temperature stability, high thermal conductivity, good mechanical properties, and scalability of manufacturing processes.

Promising advanced soft magnetic materials with high saturation magnetization at higher frequencies, low coercivities, and/or high electrical resistivity include metal/amorphous nanocomposites, which are essentially metallic nanocrystals embedded in a metallic glass matrix. Such nanocomposites with crystallites less than approximately 20–30 nm, when suitably annealed, exhibit dramatically lower losses compared with conventional materials. Materials engineering can modulate the permeability of a magnetic core to achieve more-uniform magnetic flux and thus enhanced thermal robustness. For RF applications, operation at several tens of gigahertz requires use of ferrite materials, for which various on-wafer integration approaches are being explored.

For RF applications, the critical metric is operation at several tens of gigahertz. Higher frequencies require shifting to certain specialized ferrites. One example is use of M-type hexaferrites, in which barium/strontium are added to a ferrite crystal to break its symmetry and thus increase its magnetic resonance frequency. This approach works well, but requires the presence of an attached permanent magnet. This requirement is a major limitation to practical application. Recently demonstrated self-biasing of the ferrite by use of crystal anisotropy may overcome this limitation.

New dielectric materials are needed as passivation layers and gate dielectrics for UWBG devices. These materials must have high dielectric constants, low bulk defect and interface-state densities, adequate band offsets with the UWBG semiconductors, and good stability. Successful dielectric deposition depends on the starting surface termination and the final interfacial chemistry. Novel high-k dielectrics, such as barium oxide and the fluorides calcium fluoride and magnesium fluoride, are currently being investigated because of their unusually large bandgaps of greater than 9 eV. Aluminum oxide is also being investigated for use on SiC and Ga₂O₃, but to date suffers from high leakage current.

A different class of dielectric materials is needed for use in capacitors for energy storage at the circuit level. UWBG semiconductors will enable higher frequencies (potentially hundreds of MHz), higher voltages (tens of kV), and higher operating temperatures (greater than 200 °C), which will result in more efficient power conversion. The suitability of a capacitor material depends on prevailing conditions, that is, on the combination of frequency, voltage, and temperature. The state-of-the-art dielectric for such applications is biaxially oriented propylene. For polymer-film dielectrics in general, synthesis and processing to achieve the correct morphology, crystallinity, and purity over a large area of uniform thickness are critical. Incorporation of electrodes is integral to the functioning of the capacitor. High-temperature dielectrics and low-loss materials are desired for high-repetition-rate operation. For millisecond-timescale discharge capacitors, dielectric films with metallized film electrodes meet the requirements.

Required beyond achieving good dielectric films are electrode designs that allow for high current-carrying capability, equivalent series resistance, and breakdown strength. In most applications, long life and high-voltage operation necessarily rely on self-healing of the dielectric film. Any of the new dielectric films must be validated in a number of steps to assure their commercial viability. The report notes weakening of the chemical industrial base and low levels of funding in the United States must be addressed to foster development of improved dielectric materials.

Applications

The final section of this report considers additional applications of UWBG semiconductors. Optoelectronics based on AlGaN and electronics based on many UWBG semiconductors are discussed. Considerable attention focuses on applications of interest to the US Navy and Air Force, Defense Advanced Research Projects Agency, and DOE.

AlGaN UV optoelectronics can positively impact DOD missions by reducing the size and cost and increasing the durability of photomultiplier tubes, UV lasers, and UV lamps. Targets for performance are discussed for bio-detection, identification of chemical/biological/explosive species, water purification, decontamination, non-line-of-sight communications, radioisotope power sources, photolithography, and quantum information processing.

By 2030, prediction is 80% of electricity will flow through power electronic converters. The wide-bandgap semiconductors GaN and SiC will be used extensively in the near term. Longer-term improvements require use of UWBG semiconductors.

Compact power systems are required to enable future payloads in applications such as the Navy's electric warships. As the power demand increases, the ship weight increases very quickly if using currently available electric architectures. As an example, the weight of the Navy's electric warship, DDG-1000, with 80 MW of power, is expected to reduce from 15 KT to approximately 8 KT by replacing current electric architectures with new, compact and efficient ones. Shipboard power conversion applications include AC-DC and AC-AC converters, electric propulsion drives, electromagnetic aircraft launching and recovery systems, point-of-load power converters for distribution systems, auxiliary motors and drives, high-energy weapon systems, pulsed-power systems, and electronic-support-warfare systems. The power converters of the future will first transition from Si to SiC to enhance power density and efficiency. UWBG materials, devices, and modules are expected to play important roles in DOD applications for which SiC would be inadequate.

Parasitics impose challenges to packaging of UWBG semiconductors. Three-dimensional integration should solve many problems by shorter, low-inductive connections and commutation cells. Major challenges are, however, faced for high-current (100 A), -voltage (1200 V), and -temperature (>150 °C) operation.

Use of Ga₂O₃ for high-power switching and RF electronic applications is expected to improve military aircraft power systems markedly and address power-density challenges, as operating voltages come to exceed 1 MV. Power management

systems are expected to simplify, and thus become lower cost and more sustainable. Ga_2O_3 is expected to impact the low-to-medium voltage range of less than 1.2 kV for military aircraft generators and possibly battery-powered unmanned systems. Projected RF applications include the development of class E amplifiers and integration of UWBG with GaN to improve operation by on-chip power management for RF circuits.

First-generation shipboard power-electronics building blocks (PEBBs) built by General Electric made use of commercially available 1.7-kV SiC devices. Future developments will include transformer input and output H-bridges, with integrated transformers and internal water cooling. Future PEBB units would require all four H-bridges, no external water connectors, and simplified electrical and mechanical connections. UWBG technology may meet the new requirements. Moreover, high-frequency magnetics and highly integrated PEBB-based converters will be required to realize desired power-electronic power distribution system concepts.

Additional examples of circuits for application of UWBG semiconductors include flying capacitor converters, AC–AC matrix converters, soft-switching converters, universal converters, transistor-less DC–DC converters, current-source inverters, solid-state circuit breakers, and direct solid-state transformers. Mid-voltage DC markets require development of novel DC circuit-breaker technologies operating in the range of 1.5–100 kV. These technologies should find application in grid resiliency, renewable and storage interconnection, electric aviation, electric ships, and oil and gas production.

UWBG materials such as BN and diamond could also be of interest in applications such as neutron detectors as diamond diodes continue to be developed.

1. Introduction

Authors: R Kaplar (Sandia National Laboratories [SNL]) and J Simmons (SNL, retired)

1.1 Gallium Oxide

A number of excellent review articles have been published recently, which are referenced later in this report. Most of the work to date on gallium(III) oxide (Ga_2O_3) has been on beta-phase Ga_2O_3 ($\beta\text{-Ga}_2\text{O}_3$) (simply referred to as Ga_2O_3 hereafter), although the metastable α , γ , and ε phases may also have useful properties. The high degree of interest in Ga_2O_3 has been driven largely by the ability to grown native substrates from the melt at reasonable prices. The melt-growth techniques demonstrated so far include floating zone, Czochralski, Bridgman, and edge-defined film-fed growth (EFG). The nature and direction of the surface miscut and the growth temperature strongly affect the growth rate and surface morphology. Various techniques have been used to grow high-quality epitaxial Ga_2O_3 films. These include pulsed laser deposition (PLD), metal-organic chemical vapor deposition (MOCVD), low-pressure chemical vapor deposition (LPCVD), molecular beam epitaxy (MBE), hydride vapor-phase epitaxy (HPVE), and metal-oxide catalyzed epitaxy (MOCATAXY). Silicon (Si)-doped films grown by MOCVD have achieved a mobility exceeding $180 \text{ cm}^2/\text{V}\cdot\text{s}$ at room temperature, and unintentionally doped films with background $[\text{Si}]$ in the low- 10^{15} cm^{-3} range have shown a room-temperature mobility of greater than $190 \text{ cm}^2/\text{Vs}$.

Ga_2O_3 can be readily doped n-type using controllable dopants such as Si, tin (Sn), and germanium (Ge). There have been numerous studies of defects in the material, including three types of oxygen (O) vacancies, two types of gallium (Ga) vacancies, and several types of defect complexes. The O vacancy, V_O , is believed to be a deep n-type donor, while the Ga vacancy, V_Ga , and its complexes are energetically favorable. Background impurities such as Si and hydrogen (H) can significantly impact conductivity. Further, compensation can occur particularly at higher doping levels and requires further study. Techniques such as deep-level transient spectroscopy (DLTS) and deep-level optical spectroscopy (DLOS) have been used to study the defects in Ga_2O_3 , and have revealed universal defects at $E_\text{C} = 0.8 \text{ eV}$ and $E_\text{C} = 4.4 \text{ eV}$, as well as others that depend in factors such as the growth technique, doping, and so on. Much more work is required to fully elucidate the properties of defects in Ga_2O_3 .

In addition to pure Ga_2O_3 , narrower-bandgap $(\text{Ga},\text{In})_2\text{O}_3$ and wider-bandgap $(\text{Ga},\text{Al})_2\text{O}_3$ have been studied. This is complex, as the crystal structure formed can

depend on the alloy composition. Aluminum (Al)-rich $(\text{Ga,Al})_2\text{O}_3$ remains to be demonstrated experimentally. Incorporation of Al in MBE-grown $(\text{Ga,Al})_2\text{O}_3$ has been limited to around 18% based on phase stability, while MOCVD growth has resulted in a higher Al composition of 43%. Al and indium (In) preferentially incorporate on octahedrally coordinated sites.

The thermal conductivity of Ga_2O_3 is lower than that of other ultra-wide-bandgap (UWBG) semiconductors, in the range of 0.1–0.3 W/cm·K at room temperature, and much work is ongoing to improve the thermal transport. Coefficients of thermal expansion have been measured along the various crystallographic directions.

Extensive progress has been made on Ga_2O_3 devices in the past few years. The high breakdown-field strength in the range of 6–8 MV/cm has resulted in impressive results for unipolar power devices. Additionally, modulation doping and the formation of a high-mobility 2-D electron gas (2DEG) in $(\text{Ga,Al})_2\text{O}_3/\text{Ga}_2\text{O}_3$ heterostructures have been demonstrated. Processing innovations are also critical for device fabrication and have also occurred. For example, various advances have been made in etching techniques, with a metal-assisted chemical etching having been used to fabricate Ga_2O_3 fin arrays. In addition to power devices, optoelectronic devices such as solar-blind photodetectors are of interest.

1.2 AlGaN and Related Nitride Materials

The aluminum gallium nitride (AlGaN) alloys are exceptional because they offer 1) tunable direct bandgaps spanning from 3.4 to approximately 6.0 eV, equivalent to light emission at wavelengths from 215 to 365 nm, 2) high breakdown fields potentially greater than 10 MV/cm, 3) high electron mobilities up to 1000 $\text{cm}^2/\text{V}\cdot\text{s}$, 4) high saturation velocities potentially greater than 10^7 cm/s, and 5) relatively easy n-type doping with Si.

For MOCVD-grown power transistors, these parameters offer significant advantages over Si, gallium arsenide (GaAs), silicon carbide (SiC), and gallium nitride (GaN), including a higher unipolar figure of merit (FOM). Quasi-vertical $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ PiN diodes have demonstrated greater than 3-kV reverse voltages with less than 1- μA leakage current. Challenges for AlGaN switching transistors include achieving higher blocking voltages, lower reverse leakage currents, and vertical device geometries.

While new statistical methods of modeling of AlGaN alloys better capture experimental data, including the wide spread of the bowing parameter, theoretical foundations need to be improved, especially understanding of defects. Specific

experimental test structures are needed to precisely measure material properties and validate theoretical models.

A new area being explored is transition metal nitride/III-N alloy heterostructures grown by MBE. They are challenging to grow due to an abundance of different phases, but they offer beneficial properties such as high spontaneous polarization, piezoelectric response, dry-etch resistance, and even superconductivity, enabling novel device concepts.

The development of aluminum nitride (AlN) single-crystal substrates continues to advance, with high crystalline quality, UV-C transparent 2-inch-diameter wafers being used in LED production, which is the current state of the art. The cost is comparable to semi-insulating SiC substrates, but should drop by approximately 10 times in the foreseeable future due to high-volume production. AlN substrates have much lower threading dislocation density than do AlN templates grown on sapphire, enabling UV-C LEDs with superior performance, and also recently enabling the world's first UV-C laser diode. Since they utilize a flip-chip architecture, substrate UV-C transparency is a key parameter. Remaining challenges include reducing point defect densities and addressing their apparent mobility under high current operation. The SARS-CoV-2 (COVID-19) has caused the surface disinfection market for UV-C light emitters to grow dramatically.

Finally, AlGaIn is uniquely suited as a platform for photonic integrated circuits (PICs) operating in the UV and visible, due to its UWBG, optical transparency from 0.21 to 13.6 μm , excellent nonlinear optical properties (high electric susceptibilities $\chi^{(2)}$ and $\chi^{(3)}$), high thermal conductivity, and high radiation tolerance. III-N micro-ring resonators can operate from the UV to the IR. Since the indium aluminum gallium nitride semiconductors are used for both optoelectronic and electronic devices, it may be possible to achieve compact, deployable PIC systems for positioning, navigation, and timing that are based on trapped atomic ions having electronic transitions in the UV/visible range.

1.3 Diamond

Diamond is unique among semiconductors in that it offers unsurpassed thermal conductivity combined with good mobilities and saturated velocities for both electrons and holes, together with a high breakdown field due to its large bandgap of 5.5 eV. It has long been recognized as having great promise for power switching and RF amplification, and is now beginning to emerge in these areas as well as in other novel applications.

Several types of metal-insulator-semiconductor field-effect transistors (MISFETs) have been recently demonstrated using various surface treatments and insulators on diamond channels and have demonstrated channel current densities as high as 700 mA/mm and maximum unity-current-gain frequencies (f_T) and oscillation frequencies (f_{max}) as high as 75 and 120 GHz, respectively. Improved ohmic-contact technology is now available in diamond with contact resistances as low as 0.49 Ω -mm with excellent adhesion. Historically, the stability of diamond surfaces and insulator/diamond interfaces was an issue, but recent passivation methods have shown stability in channel-current density in tests beyond 200 days in MISFETs. Further, using a wafer-bonding or grafting technique, heterojunction bipolar transistors (HBTs) have been demonstrated having emitter and base layers made of aluminum gallium arsenide (AlGaAs)/GaAs and Si/Ge, which are bonded to diamond layers serving as the collector. Values of DC current gain (β) of 311, f_T of 30 GHz, and f_{max} of 115 GHz at a collector-emitter voltage V_{CE} of 3.5 V have been measured.

Work to develop diamond diodes for power switching and particle detection has also been progressing. Blocking fields and voltages of 3.9 MV/cm and 1840 V, respectively, have been demonstrated and current densities as high as 2700 A/cm² at room temperature have been shown. Diamond diodes used as neutron detectors showed high efficiency with negligible effects from radiation damage and background X-ray fluences.

The successes of Si-, GaAs-, indium phosphide (InP)-, and GaN-based electronics in the past have all relied on the availability of relatively large-area, low-defect substrates that could be used to fabricate devices using photolithography in a semiconductor fabrication facility. Wafer size has been an important challenge for diamond, but recent progress is showing potential pathways toward larger-area diamond substrates. In 2017, the University of Augsburg in Germany reported the plasma-chemical-vapor-deposition (CVD) growth of a 92-mm-diameter, 1.6-mm-thick single-crystal layer of diamond on a Si substrate. This large diamond wafer is an incredibly important existence proof that such diamond wafers are both possible and can be manufactured using inexpensive plasma-CVD tools.

Future diamond devices offer significant improvements across many diverse application spaces including high-power RF, efficient and compact power control, complementary low-voltage logic, vacuum cathodes, radiation-hard solar cells, particle detectors, and quantum information systems. Further, the future availability of large-area diamond wafers and plates will benefit thermal-management needs in many areas apart from electronics as well.

1.4 Thermal, Magnetic, and Dielectric Materials

To fully realize the advantages of UWBG semiconductors at the system level, several classes of complementary materials must be concurrently advanced. The higher power densities of UWBG semiconductors will require improved thermal materials and interface designs, calling for a co-design approach. Understanding heat generation and flow profiles is aided by in-situ Raman thermometry, steady-state thermo-reflectance (SSTR) imaging, and IR thermography. Strategies for dealing with heating issues in high electron mobility transistors (HEMTs) include flip-chip approaches and applying cooling from the top side using jet-impingement of a dielectric fluid.

The higher frequencies of active UWBG power devices will require new passive power electronic components. Advanced soft magnetic materials are required to enable UWBG semiconductors to achieve their promised high power densities and switching frequencies, enabling enormous reductions in the size and weight of inductors, transformers, and electric machines. Promising advanced soft magnetic materials with high saturation magnetization at higher frequencies, low coercivity, and/or high electrical resistivity include metal/amorphous nanocomposites, and “permeability engineering” modulates the permeability of a magnetic core to achieve more uniform magnetic flux, enhancing thermal robustness. For RF applications, operation at several tens of gigahertz requires the use of ferrite-type materials, for which different on-wafer integration approaches are being explored.

New dielectric materials are needed as passivation layers and gate dielectrics for UWBG devices. These must have high dielectric constants, low bulk defect and interface state densities, adequate band offsets with UWBG semiconductors, and material stability. Novel high-k dielectrics such as barium oxide (BeO) and the fluorides calcium fluoride (CaF₂) and magnesium fluoride (MgF₂) are currently being investigated due to their unusually large bandgaps of greater than 9 eV. Atomic layer deposition (ALD)-deposited aluminum oxide (Al₂O₃) is also being investigated for use on SiC and Ga₂O₃, but presently suffers from high leakage current.

A different class of dielectric materials is also needed for use in capacitors for energy storage at the circuit level. UWBG semiconductors will enable higher frequencies (potentially hundreds of MHz), higher voltages (tens of kV), and higher temperatures (200 °C or more) for more efficient power conversion. Different capacitor materials have different suitability depending on how conditions (high frequency, voltage, and temperature) are combined, with the current state of the art being biaxially oriented propylene. For polymer-film dielectrics in general, synthesis and processing to achieve the correct morphology, crystallinity, and

purity over a large area of uniform thickness are critical, as is incorporating the electrode as an integral part of the capacitor.

1.5 Applications

UWBG semiconductors are of major interest for components such as power converters, and devices of this type are a key for their successful development. This is particularly interesting considering that electricity composes 40% of US energy consumption, and it is predicted that by 2030, 80% of electricity will flow through power electronic converters. GaN and SiC technologies are expected to make a major contribution in this area, through devices and circuits that operate up to 20 kV. UWBG semiconductors may be necessary beyond this. UWBG materials such as diamond could also be of interest in applications such as neutron detectors.

Compact power systems are required to enable future payloads in DOD applications such as the Navy's electric warships. As the power demand increases, the ship weight increases very quickly using the currently available electric architectures. The weight of the Navy's electric warship, DDG-1000 with 80 MW of power, is expected to be reduced from 15 KT to about 8 KT by replacing the current electric architectures with new, more compact and efficient ones. Shipboard power conversion applications include AC–DC and AC–AC converters, electric propulsion drives, electromagnetic aircraft launching and recovery systems, point-of-load power converters for distribution systems, auxiliary motors and drives, high-energy weapon systems, pulsed-power systems, and energy storage (ES) systems. The power converters of the future will transition from Si to SiC to enhance power density and efficiency. UWBG materials, devices, and modules are expected to play an important role in DOD applications beyond this.

As discussed previously, a new and promising UWBG candidate material for high-power switching and RF electronic applications is Ga_2O_3 . It is expected to dramatically improve military aircraft power systems and address power-density challenges as requirements continue to trend upward toward 1 MW and beyond. Power management systems are expected to simplify by being lower cost and more sustainable. $\beta\text{-Ga}_2\text{O}_3$ is expected to have impact in the low-to-medium voltage range (<1.2 kV) to cover military aircraft generator voltages and possibly battery-powered unmanned systems. RF amplifier applications include the development of class E amplifiers and integration with GaN to improve RF operation by on-chip power management for RF circuits. Ultimately, other UWBG materials such as diamond are expected to have the most impact on future RF systems due to its unsurpassed thermal conductivity and ability to support high electric fields and power. Ultimately, other UWBG materials such as diamond are expected to have

the most impact on future RF systems due to its unsurpassed thermal conductivity and ability to support high electric fields and power.

2. Beta-Phase Gallium(III) Oxide (β -Ga₂O₃) and Its Alloys

Authors: H Zhao (Ohio State University [OSU]) and K Goretta (Air Force Office of Scientific Research [AFOSR])

2.1 Introduction

Research in Ga₂O₃ materials and devices continues to progress rapidly. The recent workshop focused on growth, defect studies, and device fabrication and testing. β -Ga₂O₃ remains a leader among UWBG materials, in large part because of availability of melt-grown native substrates.

A number of commercial sources supply 2-inch substrates, and larger substrates up to 6 inches have been demonstrated.¹ The metastable alpha (α -Ga₂O₃),^{2,3} gamma (γ -Ga₂O₃),⁴ and epsilon (ϵ -Ga₂O₃) phases⁵ also evince useful electronic properties, but these polymorphs have attracted less attention to date.⁶ The generic term Ga₂O₃ will henceforth be used in this report when referring to the β -Ga₂O₃ phase.

Excellent summaries of Ga₂O₃ progress—"Guest editorial: The dawn of gallium oxide microelectronics," and "A review of Ga₂O₃ materials, processing, and devices"—were published in 2018.^{6,7} Other recent reviews of interest include "Review of deep ultraviolet photodetector based on gallium oxide" and "Perspective: Ga₂O₃ for ultra-high power rectifiers and MOSFETs".^{8,9} This year, the first book on Ga₂O₃ was published.¹⁰ This discussion focuses largely on advances made over the past 3 years. Invited talks in the workshop were presented by the following speakers:

1. Kenneth Goretta/Ali Sayir (Air Force Research Laboratory [AFRL]): "Ga₂O₃ Research Programs at AFRL"
2. James Speck (University of California, Santa Barbara [UCSB]): "Development of β -(Al_xGa_{1-x})₂O₃/Ga₂O₃ Heterostructures"
3. Hongping Zhao (OSU): "LPCVD and MOCVD Growth of β -Ga₂O₃ and β -(Al_xGa_{1-x})₂O₃"
4. Joel Varley (Lawrence Livermore National Laboratory [LLNL]): "Hybrid Functional Studies of Doping in β -Ga₂O₃ and β -(Al,Ga,In)₂O₃ alloys"
5. Steve Ringel (OSU): "Defects in Gallium Oxide and their Trapping Effects in Devices"
6. Uttam Singiseti (University of Buffalo): "Ga₂O₃ Devices"

7. Jacob Leach (Kyma Technologies): “Substrate Preparation and HVPE of α - and β -Ga₂O₃ Films”

2.2 Advances in β -Ga₂O₃ Materials and Electronics

In addition to pure β -Ga₂O₃, with its bandgap of 4.5–4.9 eV, (Ga,In)₂O₃ alloys with smaller bandgaps¹¹ and (Ga,Al)₂O₃ with larger bandgaps are being developed.¹² For (In_xGa_{1-x})₂O₃ thin films with a low In content ($x < 0.15$), specimens have been reported to exhibit a monoclinic crystal structure, whereas for those with a high In content ($x > 0.8$), the cubic bixbyite phase dominates. A rhombohedral InGaO₃(II) crystallographic phase exists at intermediate values of x . For Al substitution, calculations indicate the monoclinic β -Ga₂O₃ phase is preferred when there is up to 71% Al incorporation,¹¹ which is in close agreement with experimental phase diagrams.¹³ Thin-film epitaxy of β -AlGaO with a high Al composition still requires experimental demonstration.

Ga₂O₃ wafers can be fabricated in large volumes at reasonable prices.¹⁴ Single crystals have been produced using melt-growth techniques, such as floating zone,^{15,16} Czochralski,¹⁷ Bridgman,¹⁸ and EFG.¹⁹ EFG Ga₂O₃ wafers have achieved especially high-quality results, with a full width at half-maximum X-ray diffraction (XRD) rocking curve as narrow as 17 arcsec and a dislocation density as low as $10^3 \sim 10^4 \text{ cm}^{-2}$.¹⁹ Surface miscut, the material's direction, and growth temperature strongly affect the relative growth rates and surface morphology.²⁰ Recently, β -Ga₂O₃ homoepitaxy on off-oriented (100) substrates has led to reduction of structural defects and enhanced the electron mobility.²¹

High-quality Ga₂O₃ films⁶ (Fig. 2-1) have been grown recently by PLD,²² MOCVD,²³ LPCVD,²⁴ various types of MBE,^{25,26} HVPE,^{20,27} and MOCATAXY²⁶ Comparisons among these growth techniques are summarized in Table 2.1.²⁸ A batch of (010) β -Ga₂O₃ thin films with record-high electron mobilities ($184 \text{ cm}^2/\text{V}\cdot\text{s}$ at room temperature and $4984 \text{ cm}^2/\text{V}\cdot\text{s}$ at 45 K) were demonstrated via the MOCVD growth technique using Si as a dopant.²³ For unintentionally doped β -Ga₂O₃ thin films grown by MOCVD, a room-temperature mobility of $194 \text{ cm}^2/\text{V}\cdot\text{s}$ was achieved, and the background Si concentration was well controlled at the low 10^{15} cm^{-3} level.²⁹

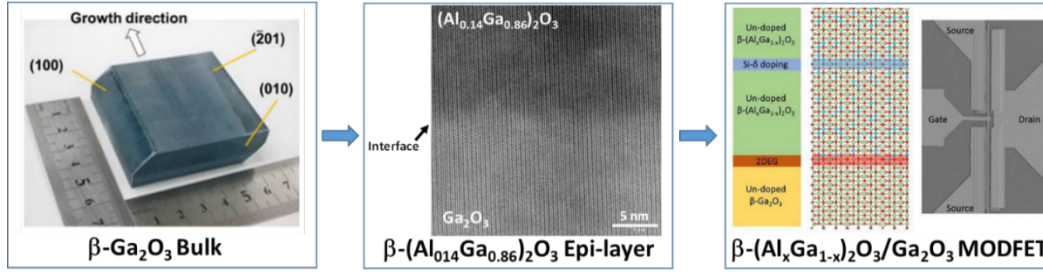


Fig. 2-1 EFG-grown β -Ga₂O₃ bulk crystal (left), atomic-resolution scanning transmission electron microscopy (STEM) image of a MOCVD-grown β -(Al_{0.14}Ga_{0.86})₂O₃ film on a β -Ga₂O₃ (010) substrate (middle),²⁸ and β -(Al_xGa_{1-x})₂O₃/Ga₂O₃ modulation-doped field-effect transistor (MODFET) device (right)³⁰

Table 2-1 Summary of some recent of Ga₂O₃ film growths²⁸

	MBE	MOCVD	HVPE	LPCVD
Growth pressure	Ultrahigh vacuum	< 100 Torr	Atmospheric pressure	< 20 Torr
Precursors	Ga cell, RF plasma oxygen, ozone	TMGa, TEGa, Ga(DPM) ₃ , O ₂ , H ₂ O, N ₂ O	Ga + HCl, O ₂	Metallic Ga, O ₂
Growth rate	~ 150 nm/hr (~ 300 nm/hr MOCATAXY)	~ 1 μm/hr (much faster if close coupled showerhead design is used)	1 ~ 10 μm/hr	1 ~ 10 μm/hr
Primary growth orientation	(010)	(010)	(001)	(010)
Other reported growth orientation	(100), (001), (-201)	(100)	(010)	(001), (-201)
Dopants	Ge, Sn, Si	Si, Sn	Si	Si
Doping range (cm⁻³)	10 ¹⁶ ~	10 ¹⁵ ~	10 ¹⁵ ~	10 ¹⁶ ~
Transport	140 cm ² /V·s (RT)	194 cm ² /V·s (RT) > 10 ⁴ cm ² /V·s (LT)	150 cm ² /V·s (RT) > 5000 cm ² /V·s (LT)	150 cm ² /V·s (RT) 600 cm ² /V·s (LT)
AlGaO growth	Al composition up to 26% for β phase	Al composition up to 40% for β phase	N/A	N/A

Studies on the growth of single-crystalline β -(Al_xGa_{1-x})₂O₃ thin films are still limited. Previous studies from MBE growth indicated that the phase stability of Al₂O₃ in β -Ga₂O₃ was limited to approximately 18% due to the formation of an aluminum gallium oxide (AlGaO₃) intermediate compound at temperatures of 600–800 °C.³¹ A recent report on the MOCVD growth of AlGaO showed Al incorporation up to 43%, based on optical transmission spectra measurements.³² The MOCVD growth technique can be promising to develop high-Al β -(Al_xGa_{1-x})₂O₃ due to its capability of higher growth temperatures. Recently, (010) β -AlGaO with an Al composition of up to 40% was demonstrated by MOCVD. As the Al composition increased, phase transformation to the γ -phase was observed.³³ Ga₂O₃ is readily n-doped and ohmic and Schottky contacts can be formed for electrical characterization and device fabrication. Standard, controllable dopants

include Si, Sn, and Ge. Iron (Fe) and magnesium (Mg) incorporation promote the formation of an insulating phase. Dopants and defects in Ga₂O₃ have been studied extensively. Monoclinic Ga₂O₃ hosts three types of O vacancies (V_O), two types of Ga vacancies (V_{Ga}), as well as various defect complexes.³⁴ V_O is assumed to be a deep n-type donor for all three sites. Recent theoretical work³⁵ and experiments indicate V_{Ga} and its complexes are favorable, particularly in O-rich Ga₂O₃. Al and In preferentially incorporate on octahedrally coordinated sites, and Al incorporates more favorably than In. Background impurities such as Si and H play a dominant role in electrical conductivity, and higher doping levels induce more compensation. The extents of compensation in Ga₂O₃ and its alloys require further study.

Defects have been studied theoretically and by use of techniques such as DLOS and DLTS, including the effects of radiation.^{36–39} Some defect levels, such as those at E_c = 0.8 eV and E_c = 4.4 eV, appear in all specimens. The former is likely due to Fe on Ga sites, which is not affected by high-energy particle irradiation. The latter seems to be independent of radiation and appears even in low-doped specimens; its cause has yet to be determined unequivocally. A defect at E_c = 0.7 eV appears to be intrinsic. Another defect at 2.0 eV scales with the Sn doping; STEM studies suggest a Ga divacancy-interstitial cluster.³⁷ Using a combination of DLOS, DLTS, and admittance spectroscopy (AS), recent studies have revealed a large reduction in the overall trap concentration in MOCVD-grown Ga₂O₃, as compared with all prior studies to date on the full bandgap spectrum of defects made on materials grown by plasma-assisted molecular beam epitaxy (PAMBE) and EFG.⁴⁰ Considerably more research is required to characterize defects and doping in Ga₂O₃.

The thermal properties of Ga₂O₃ are anisotropic and complex.⁴¹ The experimental thermal conductivity values of Ga₂O₃ are 0.1~0.3 W/(cm·K) at room temperature, which is at least 1 order of magnitude lower than those of other UWBG semiconductors. Efforts continue to design devices to maximize thermal transport, including the incorporation of high-conductivity substrates in device architectures.¹⁴ Thermal expansion, in-plane thermal strain of various material combinations, and their effects on the device's properties have been reported recently.^{42,43} The coefficient of thermal expansion (CTE) values along the a, b, and c axes of the monoclinic cell are $3.77 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$, $7.80 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$, and $6.34 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$, respectively, and the CTE along the direction of the angle between a and c axes has been determined to be $1.31 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$. All CTE values were reported to be linear under the temperature regime between room temperature and 1000 °C.⁴³

The recent workshop of UWBG semiconductors included a talk on devices.⁴⁴ From an electronics perspective, the large bandgap of Ga₂O₃, which has a high

breakdown electric field of $\approx 6\text{-}8 \text{ MV cm}^{-1}$, is its most useful property, in particular with respect to unipolar power device applications.⁴⁵ A review of recent achievements in devices is beyond the scope of this report. Advances of note in progress toward commercial applications for Ga_2O_3 electronics include successful modulation doping and formation of a high-mobility 2DEG at the $\beta\text{-(Al}_x\text{Ga}_{1-x})_2\text{O}_3/\text{Ga}_2\text{O}_3$ interface (Figs. 2-2 and 2-3).^{30,46}

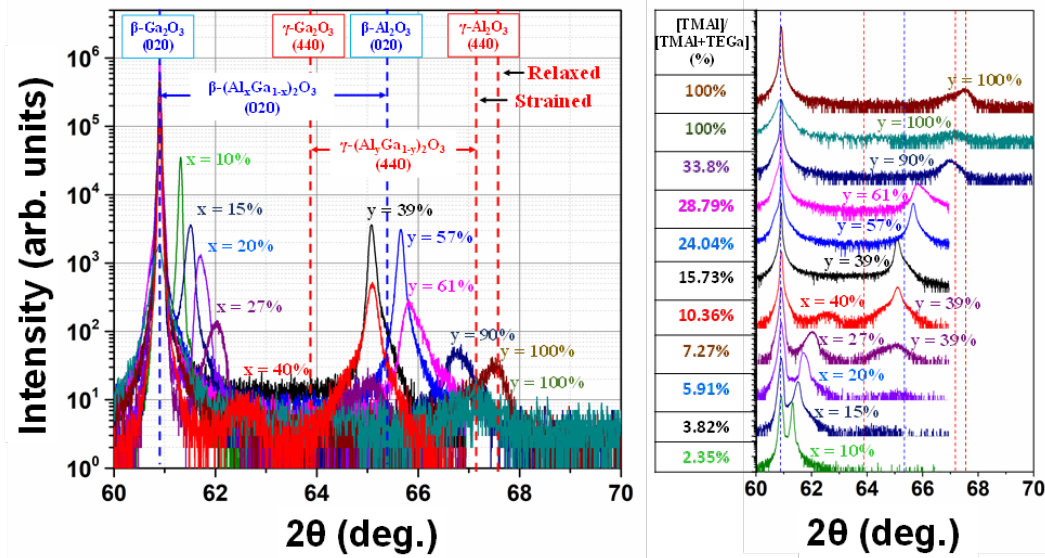


Fig. 2-2 XRD pattern for $\beta\text{-(Al}_x\text{Ga}_{1-x})_2\text{O}_3$ and $\gamma\text{-(Al}_y\text{Ga}_{1-y})_2\text{O}_3$ thin films grown on (010) $\beta\text{-Ga}_2\text{O}_3$ substrates with different Al compositions. The blue vertical dashed lines represent the 2θ peak positions for $\beta\text{-Ga}_2\text{O}_3$ (020) and $\beta\text{-Al}_2\text{O}_3$ (020), whereas red dashed lines represent the $\gamma\text{-Ga}_2\text{O}_3$ (440) and $\gamma\text{-Al}_2\text{O}_3$ (440) peak positions. XRD peaks for $\beta\text{-(Al}_x\text{Ga}_{1-x})_2\text{O}_3$ (020) films with $x = 10\%$, 15% , 18% , 27% , and 40% and $\gamma\text{-(Al}_y\text{Ga}_{1-y})_2\text{O}_3$ (440) films with $y = 39\%$, 57% , 61% , 90% , and 100% were identified.

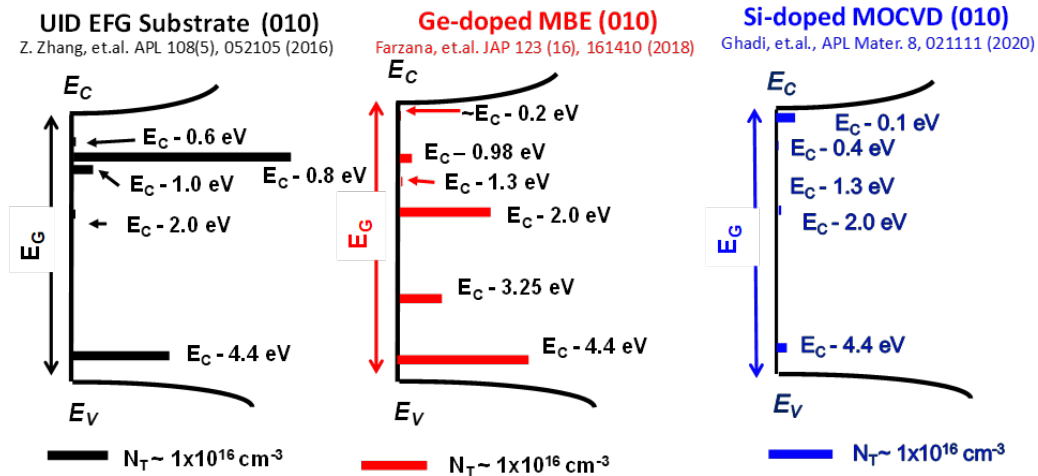


Fig. 2-3 Summary of the energy positions and concentrations for traps detected by AS, DLTS, and DLOS in $\beta\text{-Ga}_2\text{O}_3$ grown by a) PAMBE, b) EFG, and c) MOCVD at the same concentration scales. The measurement conditions used for the respective techniques were the same in each case.

Selected etching is now producing structures suitable for devices. Zhang et al.⁴⁷ report achieving near-unity ideality factor contacts for a sidewall Schottky diode. They used a hot phosphoric acid (H_3PO_4) solution (140 °C) to remove the plasma damage. The etching was strongly anisotropic. The [001] direction was found to be a favorable direction for the fabrication of vertical devices (Fig. 2-4). They envisioned being able to fabricate a range of devices, such as high-power vertical diodes, vertical transistors, and various ultra-scaled devices.⁴⁷ Huang et al.⁴⁸ produced fin arrays (Fig. 2-5) having high aspect ratios and sidewall surfaces with excellent quality on a (010) β - Ga_2O_3 substrate created via metal-assisted chemical etching (MacEtch). The etching depended strongly on the crystal orientation. Three kinds of vertical structures were formed by use of the MacEtch technique.⁴⁸

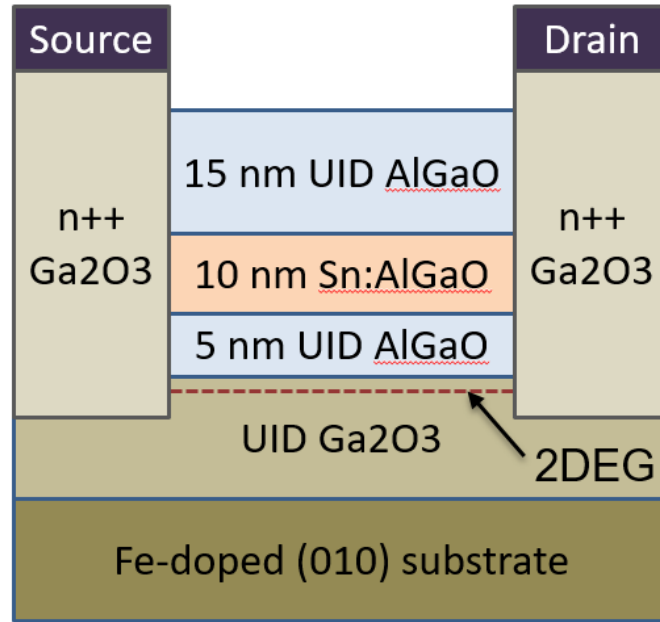


Fig. 2-4 MODFET, with controlled doping in Sn:AlGaO layer and device-level charge density greater than $1 \times 10^{13} \text{ cm}^{-3}$; goal of mobility of greater than $500 \text{ cm}^2/\text{V}\cdot\text{s}$ ³⁰

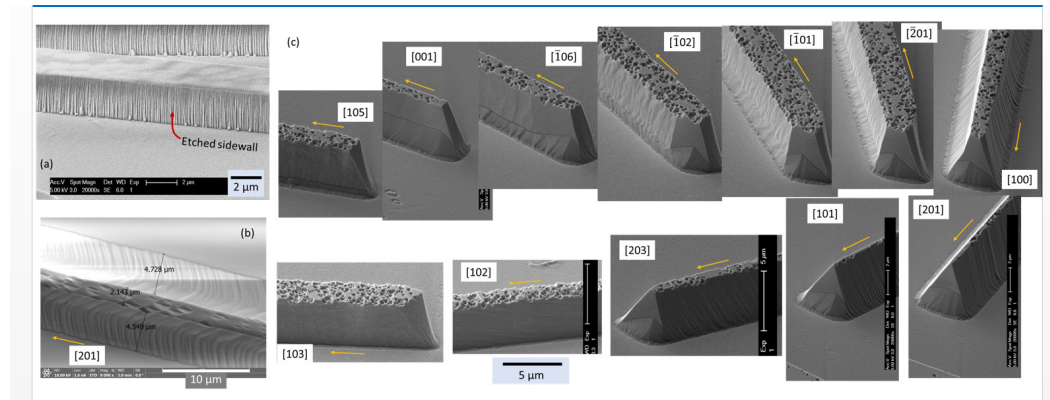


Fig. 2-5 Structures produced by anisotropic etching of Ga_2O_3 ⁴⁷

The worldwide pace of research and development in Ga₂O₃ electronics is accelerating owing to the high-power devices that are certain to find markets. In addition, optoelectronics, such as solar-blind detectors are also progressing rapidly.⁴⁹

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3. Aluminum Gallium Nitride and Related Nitride Materials and Devices

Authors: N Johnson (Palo Alto Research Center [PARC]), R Kaplar (SNL), E Bellotti (Boston University), D Meyer (Naval Research Laboratory [NRL]), A Allerman (SNL), and Leo Schowalter (Crystal IS, Asahi Kasei Corp.)

3.1 Introduction

The AlGa_N session consisted of five presentations and was chaired by Bob Kaplar (SNL) and Noble Johnson (PARC). The emphasis was on highlighting advances made since the previous workshop as well as identifying current issues and applications.

The AlGa_N alloys are UWBG semiconductors with an exceptional set of fundamental physical properties.¹ From an electronics perspective, they offer 1) direct bandgaps spanning a wide range (3.4 to ~6.0 eV), 2) high breakdown fields (>10 MV/cm for AlN), 3) high electron mobility (bulk mobilities up to 1000 cm²V⁻¹s⁻¹), 4) high saturation velocities (>10⁷ cm/s), and 5) relative ease at being doped n-type with Si (with a relatively small donor ionization energy up to ~80–85% Al content). From an optoelectronics perspective, these alloys offer direct access to emission wavelengths shorter than about 365 nm, that is, the UV-A, -B, and -C bands.

The invited talks were presented by the following speakers:

- 1) Enrico Bellotti (Boston University): “AlGa_N modeling—status quo and challenges”
- 2) David Meyer (NRL): “Epitaxial transition metal nitride/III-N alloys for next-generation electronic devices”
- 3) Andrew Allerman (SNL): “MOCVD growth of AlGa_N alloys for power transistors”
- 4) Leo Schowalter (Crystal IS, Inc, Asahi Kasei Corp.): “Development of 2-inch AlN substrates and pseudomorphic AlGa_N technology for optoelectronic, power, RF, and high-temperature applications”
- 5) Noble Johnson (PARC): “AlGa_N PIC—an introduction”

The talks emphasized summarizing advances since the previous workshop and identifying current issues and applications. Summaries of each talk are presented.

3.2 AlGa_N Modeling—Status Quo and Challenges

The session was initiated with a presentation by Enrico Bellotti of Boston University on “AlGa_N modeling – status quo and challenges”. A method that treats the alloy structural and electronic properties in a statistical fashion was presented. Rather than relying on averaging schemes like the vertex component analysis (VCA) or principal component analysis (PCA) methods, which are unable to capture the effects of the local atomic environment and the atomic configuration, the proposed approach is able to achieve a better description of the experimental data and explain the wide spread of the bowing parameter of this alloy in the literature.²

Recommendations for future work included the need to continue improving the theoretical foundation for III-nitride alloy properties and understand defects in AlGa_N (which are, for example, important for reliability of power devices). Further, a close integration between experimental and theoretical efforts is desired to validate models, quantify their uncertainty, and effectively use them for device design and performance modeling. This includes developing specific device test structures to measure relevant material properties as well as designing appropriate experiments to validate the theoretical models and to conversely verify the accuracy of the predictions of the theoretical models on realistic device structures.

3.3 Epitaxial Transition Metal Nitride/III-N Alloys for Next-Generation Electronic Devices

David Meyer reviewed “Epitaxial transition metal nitride/III-N alloys for next-generation electronic devices”. Strong motivation to explore these alloys stems from observations that several transition metal nitride UWBG semiconductors and metallic materials are lattice-matched to common III-N semiconductors, and can be grown by MBE to achieve thin epitaxial films of high crystalline quality. A challenge in experimentally synthesizing these materials is that there are often numerous phases of a given transition metal nitride compound with different crystal structures that arise with just slight changes in stoichiometry. Growth kinetics and metal-to-N flux ratios must be controlled carefully to obtain single-phase films of the desired transition metal nitride compound. Transition metal nitrides offer beneficial properties such as high spontaneous polarization,³ piezoelectric response,⁴ dry etch resistance in scandium aluminum nitride (ScAlN),⁵ and superconductivity in niobium nitride and tantalum nitride. Electrical, mechanical, and processing advantages can all be exploited to enable new device concepts. As a specific example, ScAlN can be used to produce acoustoelectric devices that leverage electronic and acoustic wave transport in a thin-film lateral device.⁶

3.4 MOCVD Growth of AlGa_N Alloys for Power Transistors

Andrew Allerman (SNL) reviewed the status of “MOCVD growth of AlGa_N alloys for power transistors”. The AlGa_N alloys offer significant advantages over Si, GaAs, SiC, and GaN for power electronics. Reflecting these advantages for AlGa_N are the high values of the critical electric field (>10 MV/cm for AlN) and of the unipolar FOM (ratio of the square of the breakdown voltage to the specific on-resistance).

Vertical device designs and fabrication strategies were reviewed for AlGa_N diodes with the following results:

- Quasi-vertical Al_xGa_{1-x}N PiN diodes ($x = 0.3$)⁷
 - Reverse voltages greater than 3000 V (at 1 mA)
 - Critical electric field (E_{crit}) = 5.9 MV/cm
- Quasi-vertical Al_{0.3}Ga_{0.7}N PiN diodes with regrown PN junctions on etched drift layers
 - Reverse voltages to 1500 V (at 1 mA)
 - Current-voltage (I-V) characteristics equal to continuously grown PN diodes
- Growth of Al_xGa_{1-x}N ($x = 0.3$) on patterned n-GaN substrates
 - Threading dislocation density of $3\text{--}5 \times 10^8 \text{ cm}^{-2}$
 - Al_{0.3}Ga_{0.7}N overgrowth greater than 12 μm achieved for vertical PN diodes
 - Vertical PIN with 30% AlGa_N: $V_{\text{rev}} = 680 \text{ V}$ (at 1 μA)

Challenges for AlGa_N-based switching transistors include achieving reverse bias junctions with multi-kilovolt blocking voltage, low reverse leakage current, and realizing a vertically conducting device geometry for high-voltage operation.

3.5 Development of 2-inch AlN Substrates and Pseudomorphic AlGa_N Technology for Optoelectronic, Power, RF, and High-Temperature Applications

Leo Schowalter (Crystal IS Inc., Asahi Kasei Corp.) spoke on the “Development of 2-inch AlN substrates and pseudomorphic AlGa_N technology for optoelectronic, power, RF, and high temperature applications”. He reviewed the unique properties and range of applications of AlGa_N as well as the status of AlN substrate development.

The AlGaN alloys are technologically the most mature of the UWBG semiconductors and offer a unique combination of properties, including the following:

- Direct bandgap
- Access to short wavelengths (down to 215 nm) for optoelectronic applications
- Very high thermal conductivity
- Very high critical electric field (>10 MV/cm)
- Easily integrated into heterojunction devices
- Capable of high temperature (>250 °C) operation

Substrate development continues to advance. The current state-of-the-art diameter for AlN single crystal wafers is 2 inches. These are of very high crystalline quality, UV-C transparent, and used in LED production. The current cost is comparable to semi-insulating SiC. A further 10 times cost reduction is foreseeable with continuing increase of wafer diameter and high-volume production.

High-quality bulk AlN substrates are enabling a wide range of new device applications:

- UV-C LEDs are a commercial product
- UV-C lasers (recent breakthrough demonstration of a UV-C laser diode at 271 nm)⁸
- High-performance and/or low-cost UV-C solid-state detectors
- High-power RF (W band or millimeter wave)
- High-power switches
- High-temperature operation for harsh environment devices

The following are specific device advancements and applications that illustrate the maturity and opportunities for AlGaN-based devices.

3.5.1 Progress on Short-Wavelength UVC LEDs

The improved material quality of pseudomorphic $\text{Al}_{1-x}\text{Ga}_x\text{N}$ on high quality AlN substrates has enabled shorter-wavelength UV-C LEDs with superior performance in the 235-nm wavelength range.⁹ A key point is that we have been able to establish somewhat better external quantum efficiency (EQE) than devices fabricated on AlN

templates grown on sapphire substrates, which have much higher threading dislocation densities. More importantly, the wall plug efficiencies are much better because of the lower operating voltages and the lifetimes are long enough to allow practical applications.

Since current UV-C LED production uses a flip-chip approach, where the radiation is extracted through the substrate, transparency of the AlN substrates is a key parameter. As shown in the Fig. 3-1, further improvement in the bulk AlN transparency has been achieved by paying careful attention to point defect introduction particularly through impurities such as carbon (C) and O. In the graph in Fig. 3-1, the intrinsic bandgap of the AlN can be detected at around 210 nm.

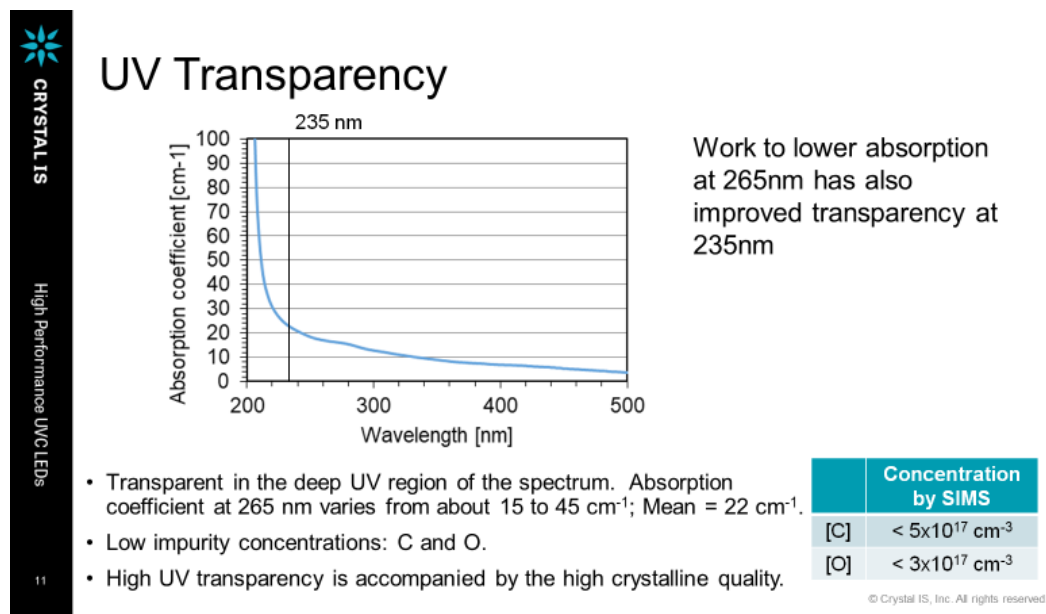


Fig. 3-1 UV transparency of AlN substrate

A key observation in high Al-content epitaxial Al_{1-x}Ga_xN (observed by several groups) is that the point defect density tends to be higher as the Al content of an epitaxial layer increases. These point defects seem to be mobile under high-current operation and can drastically reduce the performance of the short wavelength UV-C LEDs, although the device can stabilize after continued operation.⁹ At least one source of the point defects is O contamination of the high Al-content layers. It seems likely that there are others. This issue will need to be addressed to achieve practical high-power devices in UWBG Al_{1-x}Ga_xN devices.

3.5.2 Demonstration of UV-C Laser Diode

In fall 2019, the team from Asahi Kasei, Crystal IS, and Nagoya University succeeded in making the world's first UV-C laser diode.⁸ There were two key

developments that enabled this accomplishment. One was the realization of very-high-quality pseudomorphic AlGa_N layers on AlN substrates, and the other was development of hole injection by using a graded, undoped Al_{1-x}Ga_xN layer that was used to conduct holes from the p-type GaN contact. Both innovations have the potential to lead to other improved electronic and opto-electronic devices based on the UWBG pseudomorphic AlGa_N/AlN material system.

3.5.3 UV-C LED Applications to COVID-19 Disinfection

The surface disinfection market has grown dramatically since the COVID-19 pandemic burst on the world stage in early 2020. This has dramatically increased demand for UV-C LEDs especially in the 260- to 270-nm wavelength range. Many companies are now selling products which incorporate UV-C LEDs to disinfect masks and other personal protective equipment and medical equipment. Other applications include providing greater safety living in a world where the COVID-19 virus remains uncontained and where greater protection against other pathogens is desired. The key point here is that the 2-inch AlN substrates that are currently in production have enabled volume production (ramping toward hundreds of millions per year) while the cost per milliwatt is dropping below \$0.05/mW in volume. Of course, the price is still very high priced compared to blue LEDs, so there is still a long way to go in terms of initial cost of efficiency (the highest wall-plug efficiency available in volume production is around 5%).

3.6 AlGa_N PIC—An Introduction

The session concluded with a brief presentation by Noble Johnson (PARC) on “AlGa_N PIC—an introduction”. The key message was to highlight AlGa_N as a photonic material that is uniquely suited as a platform for PICs operating in the UV and visible spectral bands.

Several recent studies have explored the implementation of AlN for on-chip optical waveguides and micro-resonators and the potential benefits.^{10–12} The desirable properties of AlN include UWBG (~6.0 eV), wide spectral window of optical transparency (0.21 to 13.6 μm), excellent nonlinear optical properties including electric susceptibilities $\chi^{(2)}$ and $\chi^{(3)}$, high thermal conductivity (285 W/m-K), and high radiation tolerance. Through nonlinear frequency generation processes (e.g., four-wave mixing), III-N micro-ring resonators can support a wide spectral range from the UV to IR. Further, the AlGaInN semiconductors are the foundation of mature fabrication technologies in both optoelectronics (laser diodes and LEDs) and electronics (transistors, switches, and diodes for high-power and high-frequency applications). Applying these features would be particularly enabling for compact, deployable PIC systems for positioning, navigation, and timing that are

based on trapped atomic ions (e.g., optical atomic clocks), with the most promising of these (e.g., ytterbium [Yb^+] and strontium [Sr^+]) having relevant electronic transitions in the UV/visible bands.

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4. Diamond and Related Materials and Devices

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4.1 Introduction

This section reports on new and exciting developments in diamond electronic devices over the past 3 years, the technical challenges remaining, and the opportunities and tasks for reaping the benefits offered by diamond for electronics. Due to its high breakdown field, bipolar conduction (both electrons and holes), high mobilities, and superior thermal conductivity, diamond has long been recognized as having great promise for power switching and RF amplification, and is now beginning to emerge in these areas.

The invited talks were presented by the following speakers:

- 1) Srabanti Chowdhury (Stanford): “The roadmap to diamond—GaN to diamond for next-generation electronics”
- 2) Joe Varghese (MIT LL): “Advances for diamond RF MISFETs”
- 3) Tony Ivanov (ARL): “Current status of diamond RF transistor research at ARL”
- 4) John Albrecht (MSU): “Progress on diamond growth and devices for power electronics”
- 5) Jack Ma (University of Wisconsin): “The prospect of diamond-collector heterojunction bipolar transistors”
- 6) John Janik (Extropy, LLC): “The Extropy vision of diamond technology”

4.2 New Developments in Diamond Electronic Devices and Growth

4.2.1 Diamond Transistors

Recently US laboratories have been making good progress toward reaching and extending the state of the art in diamond transistors, a field that heretofore has been dominated by Japan and Europe. Challenges for all types of diamond transistors and diodes in the past have included poor adhesion and high resistance in ohmic contacts, and unstable surfaces and insulators in field-effect transistors (FETs) and

MISFETs. MIT LL and MSU have developed a new regrown p^+ ohmic contact having excellent adhesion with contact resistances as low as $0.49 \Omega\text{-mm}$ and an Al_2O_3 -based gate insulator having a better than 7% drift stability in current over more than 200 days with a current density (J_{DS}) sufficient for MISFETs.¹ The DEVCOM Army Research Laboratory has pioneered novel stacks of transition-metal oxides (TMOs).² Diamond transistors produced with a vanadium oxide (V_2O_5) acceptor layer show $I_{\text{DS}} = 700 \text{ mA/mm}$, $g_{\text{m}} = 140 \text{ mS/mm}$, and good stability. Together these laboratories have demonstrated US-leading J_{DS} values of 500–700 mA/mm, unity current gain frequency (f_{T}) values of 12.5–75 GHz (depending on gate length), and maximum frequency of oscillation (f_{max}) values of 16–55 GHz. Device photos, I-V characteristics, and frequency performance are shown in Figs. 4-1 and 4-2.

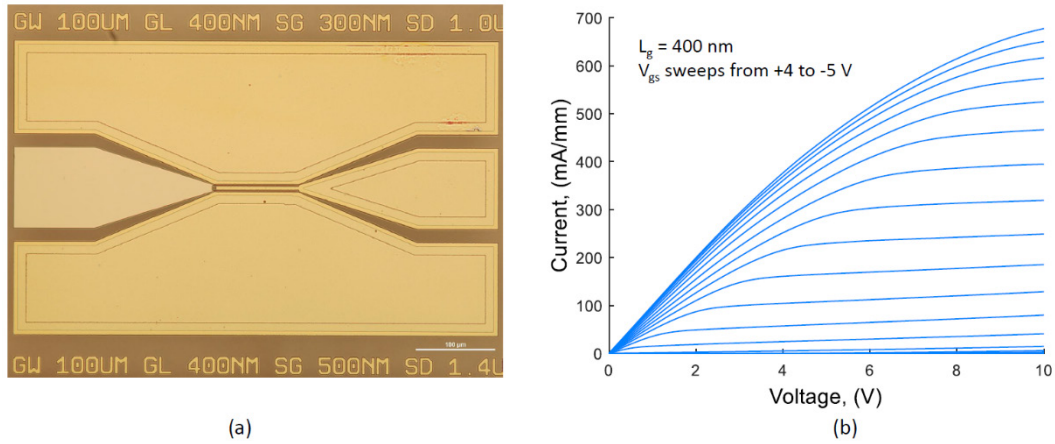


Fig. 4-1 Device photo and I-V characteristics of a diamond FET from MIT LL. Transconductances as high as 170 mS/mm have been observed to date.

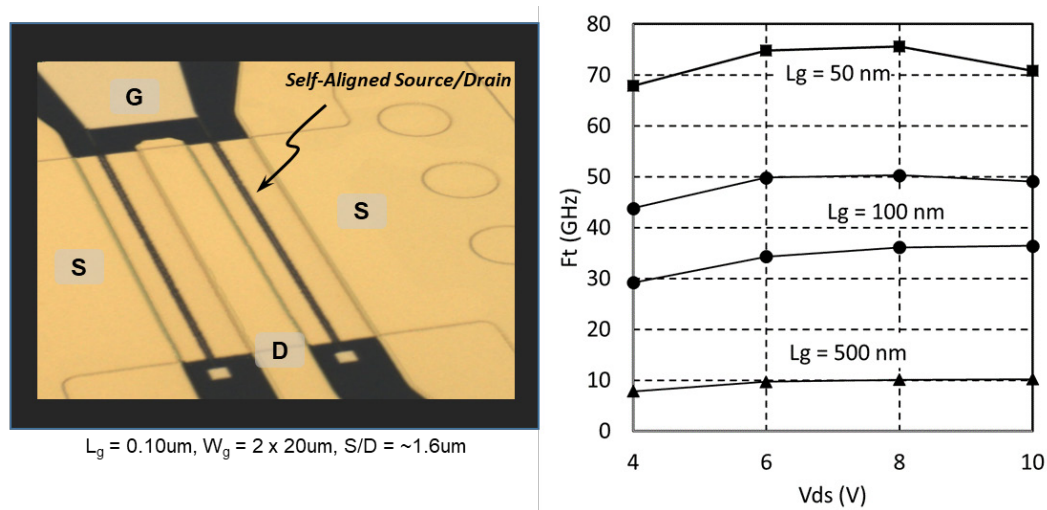


Fig. 4-2 Device photo and f_{T} performance of a diamond FET from ARL

Further, collaborators at the University of Wisconsin and MSU have demonstrated novel HBTs comprising emitter and base layers made of AlGaAs/GaAs and Si/Ge, which are bonded onto diamond layers serving as the collector. Diamond has reasonable p-type doping but non-optimal n-type doping (so far). By forming heterojunctions between diamond and other n-type semiconductors (e.g., Si, Ge, GaAs, and so on) via a bonding technique called grafting,³⁻⁶ high-performance diamond p-n diodes and other three-terminal devices such as HBTs, inversion-mode vertical power metal-oxide-semiconductor field-effect transistors (MOSFETs), and insulated-gate bipolar transistors (IGBTs) can be made to take full advantage of single-crystalline diamond. Figure 4-3 shows a grafted Si/Ge/diamond pnp HBT that features a DC current gain (β) of 311, f_T of 30 GHz, and f_{max} of 115 GHz at a collector-emitter voltage V_{CE} of 3.5 V. All of these US FET and HBT devices show great promise for RF and power-switching applications given further development.

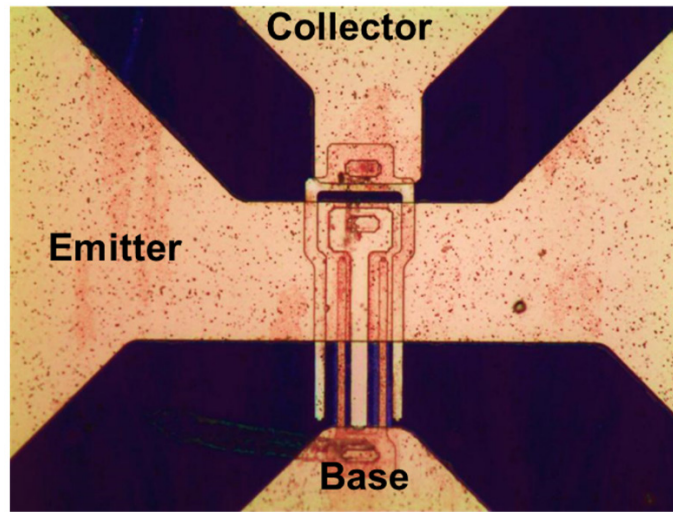


Fig. 4-3 A grafted Si/Ge/diamond pnp HBT having a DC current gain of 311, f_T of 30 GHz, and f_{max} of 115 GHz (contributed by the University of Wisconsin)

Notable transistor developments in Japan and France have also occurred in the past 3 years and bear mentioning. Epitaxial n-type, phosphorus-doped diamond layers have been used to demonstrate inverted-channel diamond MOSFETs. The lateral MOSFET structure included an Al_2O_3 gate dielectric and p^{++} boron-doped source-drain contact layers. The devices displayed a field-effect mobility of $20 \text{ cm}^2/\text{V}\cdot\text{s}$, which was apparently limited by the relatively high trap density at the insulator-diamond interface ($\sim 10^{13} \text{ /cm}^2\text{-eV}$).^{7,8} Further, a significant advance in channel mobility of H-terminated diamond FETs was shown using crystalline hexagonal boron nitride (h-BN) as a gate dielectric. The results showed a surface-channel mobility of $300 \text{ cm}^2/\text{V}\cdot\text{s}$ at a moderate carrier density of $5 \times 10^{12} \text{ cm}^{-2}$.⁹ Finally,

another MOSFET device was demonstrated based on a p-type, lightly boron-doped diamond channel that is operated in a nonequilibrium deep-depletion mode. The device structure used an Al₂O₃ gate dielectric, and electrical measurements indicated a bulk-channel mobility as high as 1000 cm²/V-s.¹⁰

4.2.2 Diamond Diodes

Work in diamond diodes for power switching and neutron detection has also been progressing. Epitaxial diamond PiN diodes fabricated at ASU showed a blocking field of 3.9 MV/cm and light emission indicating bipolar operation. The diodes employed p⁺⁺ high-pressure, high-temperature (111)-oriented substrates with boron doping greater than 10²⁰ cm⁻³, a 0.5-μm undoped diamond intrinsic layer, and an n-type layer with phosphorus doping at approximately 10²⁰ cm⁻³.¹¹ Also at ASU, thin (5-μm) diamond PIN diodes with a cubic boron nitride (c-BN) neutron conversion layer demonstrated high-efficiency neutron detection in pulse-counting mode. The diodes worked at a low applied bias (<20 V) showed negligible counts from the X-ray background and operated without degradation after exposure to a fluence of 10¹⁵ neutrons/cm³.¹²

At MSU, diamond Schottky diodes have been fabricated based on a structure that has a p⁺ layer with a titanium (Ti)/gold (Au) ohmic contact and a p⁻ drift layer with a molybdenum (Mo)/Au Schottky contact. The epitaxial diamond p⁻ layer was grown first on a low dislocation-density substrate, then the thicker p⁺ layer was grown. This sequence was chosen since growth of heavily boron-doped p⁺ layers can produce new dislocation defects that propagate into the p⁻ layer if the p⁻ layer is grown later. The p⁺ and p⁻ layers were then removed from the starting substrates and the metals deposited on both sides. The best diode showed a breakdown voltage of 1840 V and a current density at 100 °C of 300 A/cm².¹³ Heterostructure pn-junction diamond diodes have also been fabricated by MSU and the University of Wisconsin on a diamond substrate having a p-type diamond layer by first smoothing the diamond using chemical-mechanical polishing, then depositing a thin oxide layer for GaAs bonding, and finally transfer printing an n-type GaAs layer onto the diamond substrate. This pn junction showed a breakdown voltage of 1000 V and a room temperature current density of 2700 A/cm², which is quite impressive for such a developmental structure.¹⁴ Images depicting diode growth, fabrication, and testing at MSU are shown in Fig. 4-4; the MSU/Wisconsin diodes are shown in Fig. 4-5.

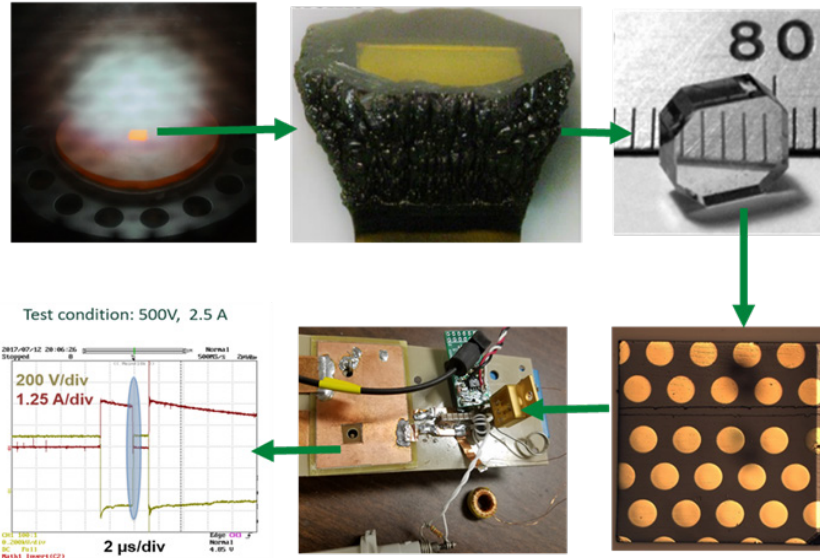


Fig. 4-4 Progression shown from diamond growth, to diode fabrication, to testing a packaged diamond diode at MSU

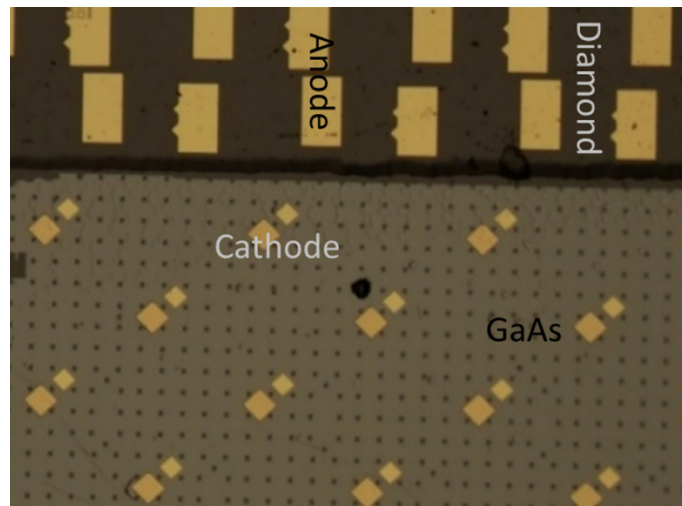


Fig. 4-5 A grafted GaAs/diamond np diode with an avalanche breakdown voltage of 1000 V and a calculated Baliga's figure of merit (BFOM) of 11 GW/cm² (contributed by University of Wisconsin)

4.2.3 Growth of Larger-Area Diamond Substrates

The successes of Si-, GaAs-, InP-, and GaN-based electronics in the past have all relied on the availability of relatively large-area, low-defect substrates that could be used to fabricate devices using photolithography in a semiconductor fabrication facility. This has been an important challenge for diamond, but recent progress is showing several potential paths toward larger-area diamond substrates. In 2017, the University of Augsburg in Germany reported the plasma-CVD growth of a 92-mm-diameter, 1.6-mm-thick single-crystal layer of diamond on a Si substrate.¹⁵

This diamond wafer, shown separated from its Si host substrate in Fig. 4-6, is an incredibly important existence proof that large-area diamond wafers are both possible and can be manufactured using inexpensive plasma-CVD tools.

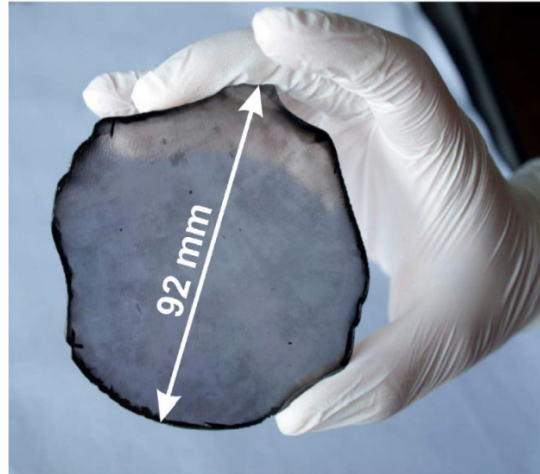


Fig. 4-6 Freestanding 92-mm diamond wafer grown at the University of Augsburg in Germany

To address the domestic need for smooth, larger-area diamond substrates for electronic applications, two new small US companies were formed in the recent past, Extropy, LLC, and Plasmability, Inc, and an existing wide-bandgap (WBG) substrate producer, Kyma Technologies, is now pursuing diamond substrate development as well. Extropy's stated goals are to develop and sell DC-plasma diamond-growth reactors (a 4-inch version is already available) as well as develop heterogeneous growth processes for single-crystal diamond layers on disparate substrates such as Si. Plasmability's growth reactor is of a novel toroidal design that enables EFG of diamond rods; scaleup to larger sizes is done by building larger reactors. Kyma is working with MSU on lateral growth from existing diamond seeds to achieve larger areas. Finally, Sinmat, Inc, has developed a chemical-mechanical polishing process for diamond that can produce a surface with near monolayer flatness, which can be important to maximize the carrier mobility in lateral devices such as MISFETs, as well as enable successful transfer printing of disparate layers as in the HBTs described earlier.

An alternative to the development of large-area, single-crystal diamond substrates is the development of a so-called mosaic technology that could bond multiple small diamond wafers in arrays on larger carrier substrates such as Si. While this approach could provide a means to process the small diamond wafers in larger semiconductor equipment, issues such as diamond-wafer planarity, orientation, and attachment remain to be worked out. To our knowledge, no one is working on this latter approach at the present time.

4.3 Technical Challenges Remaining

As has been well demonstrated by the mature Si, GaAs, and InP industries, an up-and-coming new materials/device technology ideally needs the parallel development of high-quality substrates, high-quality epitaxial growth, and a device fabrication process that is optimized for high performance with long-term reliability:

- For diamond substrates, the fledgling industry that has begun must continue with its goals of ever larger, smoother, and more defect-free substrates and must find consistent funding streams to do so. Nominally available sizes of diamond plates today range up to 10–15 mm, but must continue to push well above 1 inch to sizes that semiconductor fab lines are comfortable handling (minimally 2 inches, but sometimes larger). Not only must the surface finish ultimately be monolayer smooth, but the subsurface damage caused by polishing must be eliminated, either via a final reactive-ion etching step or other means such as noncontact chemical-mechanical polishing. Metrology methods must be developed to detect and quantify crystal defects and subsurface polishing damage and correlate them with device performance.
- For diamond epitaxy, the growth tools and processes must be continually refined to reduce the density of defects (currently 10^7 – 10^9 cm⁻²) down to levels acceptable for devices (estimated at 10^6 to 10^3 cm⁻² for lateral vs. vertical devices). Further work must be done to elucidate the best substrate tilt and offcut angles for epitaxy and standardize them with the substrate vendors for production. Additionally, the full range of available metrology tools must be consistently applied to characterize grown films to optimize their properties for devices. These tools include photoluminescence, atomic force microscopy, XRD, transmission electron microscopy, cathodoluminescence, capacitance-voltage, Hall, secondary ion mass spectrometry, and others.
- For optimized fabrication of diamond devices, it must first be noted that the diamond surface is very sensitive to its charge state or the nature of the chemical group(s) on its surface. Diamond does not readily grow a native oxide like Si does and can/will form surface bonds with most species in its environment. For this reason, diamond devices must be fabricated in a controlled environment in a specific sequence that terminates the diamond surface with a desired species (usually H) and does not perturb the H bonds later (or removes them in a controlled way). The optimal process sequence has yet to be fully worked out, but laboratories such as MIT LL and ARL are working on this as one of their highest priorities. Further, the use of ion

implantation to form ohmic source and drains regions has been a standard process in Si complementary metal–oxide–semiconductors (CMOSs) for decades, but has not yet been shown to work in diamond at reasonable annealing temperatures, though there are National Science Foundation programs looking to make it work for diamond at higher temperatures.

- Fourthly, there must be a concerted effort to refine the theory of carrier transport both at diamond surfaces next to insulators and in the bulk crystal. Carrier mobility, velocity, and device performance must be correlated to surface and bulk defects and other relevant properties such as carrier density. The metrology tools mentioned previously will be particularly important for these studies. Similarly, a better understanding of phonon transport in diamond and the magnitude/effects of thermal barrier resistances at the interfaces between diamond and other materials is also needed.

4.4 Diamond Opportunities and Tasks

The potential application spaces for diamond devices are unusually broad, as described here. In addition, diamond not only offers operation in these applications but can revolutionize the performance in many of them:

- *Ever-higher RF power for military applications:* The higher critical breakdown field and superior thermal conductivity over all other materials suggest that diamond will be the ultimate material/device for generation of RF power. Existing technologies such as GaN already struggle with heat removal and are limited to power densities substantially below their theoretical electronic limits because of this. Diamond not only has a higher electronic power-density limit than GaN, but can much more easily remove the heat from the transistor active area since the ratio of the thermal conductivities is as high as 13:1. Challenges/tasks include refining epitaxial growth methods, developing stable gate-insulator/diamond combinations, and improving channel mobility/carrier transport.
- *Novel device topologies:* As noted earlier, novel transistor topologies such as HBTs and IGBTs comprising Si, GaAs, AlGaAs, and/or SiC layers heterogeneously integrated with diamond collectors using special wafer bonding/grafting techniques are promising from a performance perspective. Challenges/tasks include a requirement for monolayer or near monolayer flatness for the two sides of the wafer-bonded interface, as well as particle-free processing for this critical wafer-bonding step.

- *Smaller power diodes/switches with low loss:* As first described by Baliga in his landmark papers on diodes for power switching^{16,17} and extended by Grotjohn of MSU,¹³ diamond offers the smallest diode thickness and size for power switching. This also offers a reduction in the size of the passive components as well as the size of the overall power-switching system compared to Si-, SiC-, and GaN-based approaches.¹⁸ Challenges/tasks include finding shallower dopants or effective dopant schemes as well as the materials-growth issues cited elsewhere here.
- *Diamond CMOS low-voltage logic:* Since diamond offers both electrons and holes as charge carriers and has higher mobility for both carrier types than in Si, low-voltage diamond CMOS logic should be possible. The Si CMOS has been the workhorse for low-power digital computation for over 50 years, but at present, the clock speeds in dense Si CMOS CPUs are limited to less than 5 GHz purely by the inability to remove a heat flux greater than 135 W/cm² out through the Si substrate. Defense Advanced Research Projects Agency (DARPA) programs such as ICECool have worked on this problem for Si CMOSs, but many of the solutions involved cumbersome and large cooling hardware. Since the clock-frequency limit in Si CMOS is given by the dynamic power (which goes as $\frac{1}{2} f_{\text{CLOCK}} C V^2$),¹⁹ one can use the heat-conduction equation $\frac{dQ}{dt} (\text{watts}) = \sigma_{\text{THERMAL}} A \frac{\Delta T}{t}$ and the respective thermal conductivity difference between diamond and Si to show how much higher the clock speed could be for diamond CMOS, shown in Table 4-1. Here we hold the device temperature T , circuit area A , substrate thickness t , and circuit densities constant for the two cases.

Table 4-1 Higher clock frequency enabled by thermal advantage of diamond

Substrate/channel material	Upper clock (switching) frequency at $\Delta V = 1 \text{ V}$
Si CMOS CPUs	~5 GHz
Diamond CMOS	~78 GHz

This comparison gives a powerful illustration of how complementary diamond digital circuits could dramatically improve the clock speed of computation. It may be that the full 78-GHz clock speed cannot be reached due to other limitations such as interconnect time delays, interconnect capacitances, or limitations in other heat-removal components, but nevertheless, diamond complementary logic could remove the present thermal roadblock to higher digital speeds. Note that some of the new DARPA Electronics Resurgence Initiative programs seek to develop 3-D integration to reduce interconnect time delays and capacitances, so perhaps

those architectures could be combined with diamond logic to approach the approximately 78-GHz clock speeds. Challenges/tasks include the further development of p-MISFETs in diamond as well as beginning in earnest the development of the complementary n-MISFETs.

- *Diamond HEMTs/MODFETs*: A number of workers^{20,21} have proposed diamond-based HEMT or MODFET structures wherein a c-BN layer is grown on a diamond channel or vice versa. The small lattice mismatch of c-BN to diamond (only 1.3%) and higher bandgap of c-BN should enable the formation of 2-D electron or hole gases in the diamond close to the interface with the c-BN barrier layer. This could yield a much higher channel mobility versus MOSFET or MISFET approaches, since the carrier wavefunctions do not see the device surface or an amorphous insulator. If the c-BN needs to be doped to induce the carrier gas, shallow dopants have been reported.^{18,22} Note also that c-BN has a high thermal conductivity as well (2145 W/m-K).¹⁸ Challenges/tasks include the development of epitaxial growth of c-BN on diamond, which will likely require proper plasma conditions to prevent formation of hexagonal BN.
- *Vacuum cathodes and vacuum FETs*: Since diamond offers a tunable negative electron affinity (NEA) at its surface,¹⁸ one can in principle tailor its properties to make vacuum cathodes and so-called vacuum FETs, where the carriers exist outside (but are attracted and held to) the diamond surface. Challenges/tasks include the control of the NEA property as well as maintaining sufficiently good vacuum to avoid poisoning the diamond surface and hindering the carrier transport.
- *Radiation-hard solar cells and neutron detectors*: Diamond is very radiation hard to protons and is relatively transparent (non-absorptive) to gamma rays; therefore, it could be potentially very useful for solar cells in the space environment and neutron detectors for various nuclear and particle-accelerator applications.^{12,23} Challenges/tasks include improving the availability of low-defect-density diamond substrates as well as epitaxial growth on them.
- *High-temperature operation*: Laboratory diamond MISFETs have been shown to operate to 400 °C,²⁴ and higher-temperature operation should be possible since the new ohmic contacts to diamond cited earlier are refractory. Challenges/tasks include perfecting the insulator/diamond interface in MISFETs for stability as well as finding the best refractory ohmic contact for the highest temperature performance.

- *Dual-use applications:* In addition to the properties and applications cited previously, diamond has other properties such as Si and N vacancy centers and others that can be exploited for dual-use applications. The associated physics are too extensive to cover here, but the applications include the following:
 - Quantum information sciences, navigation, and magnetic sensing
 - Power switching, overhead Internet, low-Earth-orbit One Web satellites, and cell towers
 - Thermal management, since flat diamond wafers could be useful for thermal applications apart from electronics

Note most diamond applications can leverage, to some extent, the large amount of gem growth occurring around the world, as there are presently over 1000 gem-growth reactors worldwide with the number increasing year by year. The goals for gem-growth development do not completely overlap with the needs for diamond devices, but nevertheless some leverage is expected as new reactor designs and processes are developed by the gem industry.

4.5 Summary and Way Forward

The combination of diamond's physical properties is unsurpassed for electronic and related devices, and the future is very bright for the performance and broad applications of these devices once developed. It should be recognized that these material/device concepts are at a very early stage of maturity, and it will likely take more than a decade to develop many to the point where the potential payoffs appear in multiple commercial products. But the large and often unique payoffs definitely merit increased development of diamond growth and devices. Suggested areas of underpinning investment include the following:

- 1) *Large-area diamond substrates:* Large 2-inch, 4-inch, and ultimately foundry-sized diamond substrates are needed to enable faster research progress as well as the use of Si-grade lithography, deposition, and etching tools for tighter control of transistor properties. Progress in 4-inch diamond-substrate demonstrations out of Germany serve as existence proofs that these are possible. Defect-free polishing methods for monolayer smoothness also require development.
- 2) *Diamond epitaxial growth:* Continued refinement of epitaxial-growth technology for high-quality, low-defect diamond films needs to be

supported, as well as the growth of related materials such as c-BN on diamond and vice versa.

- 3) *Diamond transistors and diodes, including complementary transistor designs*: As diamond offers both electrons and holes in comparable mobilities (and higher than Si), the possibility of making both high-power devices and low-voltage CMOS-like logic is very real. Two types of complementary transistors seem possible: p- and n-channel diamond MISFETs and p- and n-channel c-BN/diamond MODFETs or HEMTs. Process development and integration are still in their early stages for these devices, so they will require investment as well.
- 4) *Optimization of carrier-transport physics in diamond devices*: This includes comparative theoretical and experimental work to understand and define the unique features of carrier transport in diamond as well as the optimization of that transport in real devices.

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5. Supporting Technologies

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5.1 Introduction

In addition to research needed on the UWBG semiconductors themselves, several classes of complementary materials must concurrently be advanced to realize the advantages of the UWBG semiconductors at the system level. These include thermal management materials (and interfaces between them, at the device, package, and system levels), magnetic materials, and dielectric materials (both for integration with the UWBG semiconductors, for example, as gate dielectrics, and as energy storage materials for capacitors). The invited talks occurred in three sessions and were as follows:

- Thermal materials and interfaces
 - 1) Sukwon Choi (PSU): “UWBG material and device thermal issues”
 - 2) Gilbert Moreno (National Renewable Energy Laboratory [NREL]): “UWBG package and system thermal issues”
- Magnetic materials
 - 1) Paul Ohodnicki (National Energy Technology Laboratory [NETL]): “Magnetics for high-power applications”
 - 2) Will Harris (Northeastern University): “Ferrite based magnetics”
- Dielectric materials
 - 1) Sarit Dhar (Auburn University): “Gate and passivation dielectrics”
 - 2) Richard Jow (ARL): “Dielectrics for energy storage”

Additionally, significant material was presented by several others during the breakout session, notably Patrick Hopkins of the University of Virginia. Adam Wilson and Nathan Lazarus of ARL collected additional information on thermal and magnetic materials, respectively.

5.2 Thermal Materials and Interfaces

5.2.1 UWBG Material and Device Thermal Issues

Sukwon Choi of PSU opened the session by noting that heat dissipation in UWBG devices is a limiting factor for several of the leading candidate materials ($\text{Al}_x\text{Ga}_{1-x}\text{N}$ and $\beta\text{-Ga}_2\text{O}_3$). However, measuring the temperature profile at the hotspot of these devices is experimentally daunting. Using a combination of in-situ Raman thermometry, thermoreflectance thermal imaging, and IR thermography, the channel temperature profile can be measured. Understanding of the self-heating behavior of UWBG devices requires the knowledge of both heat generation and thermal transport mechanisms. The heat generation profile within devices can be inferred by coupled-electrothermal simulation. Phonon transport across multi-material stacks that compose UWBG devices can be characterized via optical pump-probe methods such as frequency domain thermo-reflectance. For example, the thermal resistance of a $\beta\text{-Ga}_2\text{O}_3$ /4H-SiC composite substrate is highly dependent on the $\beta\text{-Ga}_2\text{O}_3$ crystalline quality, interfacial thermal boundary resistance (i.e., what material is adjacent to it), and several other factors. The best material in the electronics point of view may end up leading to early thermal failures. Therefore, it is important to take thermal considerations into account when designing UWBG devices using $\beta\text{-Ga}_2\text{O}_3$ (and $\text{Al}_x\text{Ga}_{1-x}\text{N}$). A co-design approach is necessary to reach an optimal set of conditions for integration into a high-performing device. With optimized integration, the thermal resistance of $\beta\text{-Ga}_2\text{O}_3$ devices may be on par with that of GaN-on-Si HEMTs, and since heat generation is concentrated around the 2DEG channel, flip-chip strategies or applying cooling from the top-side may be advantageous. $\text{Al}_x\text{Ga}_{1-x}\text{N}$ devices are also promising. However, recent experiments performed in Choi's lab demonstrate that the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ thermal conductivity ($<10 \text{ W/mK}$) is much lower than previous measurements reported in literature. This value is also more than a factor of 10 times lower than those for the binary constituents GaN and AlN, due to phonon alloy-disorder scattering. However, high Al-content $\text{Al}_x\text{Ga}_{1-x}\text{N}$ devices maintain an advantage in that they perform well across a wide temperature range, as its thermal conductivity is maintained at the same value and the electrical output characteristics are insensitive to the increase in the environment temperature.

5.2.2 UWBG Package and System Thermal Issues

The next talk was presented by Gilbert Moreno of NREL and covered UWBG package and system thermal issues with a focus on Ga_2O_3 . Efficient thermal packaging approaches are especially important for realizing Ga_2O_3 power electronics. While Ga_2O_3 is extremely attractive for power electronics due to both

a very high FOM (~10 times larger than Si) and very low cost (device production costs predicted to be two to four times lower than SiC), it suffers from a very low thermal conductivity, only approximately 15 W/m-K. This is far lower than SiC (210 W/m-K) and even than Si (92 W/m-K). Fortunately, new approaches in thermally dissipative package designs are providing ways to circumvent this shortcoming. Recent designs utilize an impingement jet of dielectric cooling fluid on the electrical interconnects/busbars of a MOSFET and achieve heat transfer coefficients of 23,000 W/m²K with modest jet velocities of 0.3 m/s (Figs. 5-1 and 5-2).¹ Double-sided jet impingement cooling is currently being explored as well.² These results represent significant progress toward the Department of Energy Vehicle Technologies Office 2025 automotive power density goals of 100 kW/L at a cost of \$2.70/kW.³

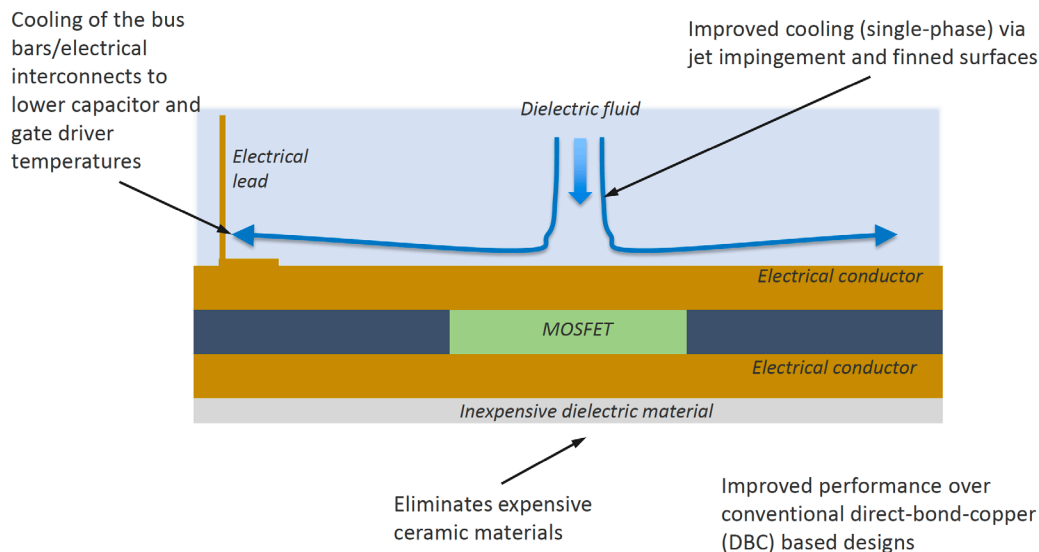


Fig. 5-1 Schematic diagram of the jet-impingement cooling technique

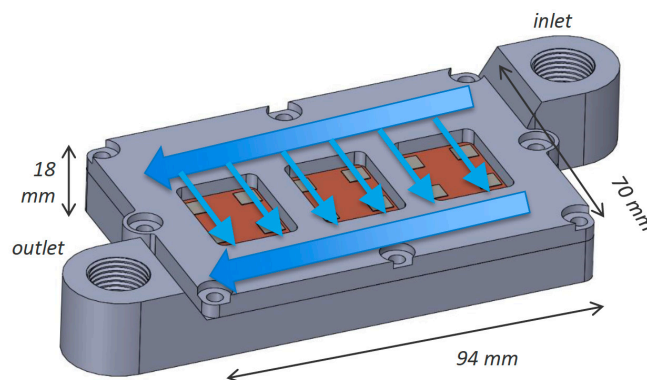


Fig. 5-2 CAD model of the jet impingement cold plate fluid manifold designed to cool 12 MOSFET devices

During the breakout session, Patrick Hopkins of the University of Virginia pointed out that thermally conducting materials and heat dissipating architectures will play an increasingly important role as UWBG materials are further developed and begin to be incorporated within power electronics. A major challenge is developing more-accurate techniques for measuring thermal conductance, and particularly of thermal transport across interfaces. A new technique, SSTR, has been developed for measuring thermal conductivity of bulk substrates and thermal conductance across bulk interfaces.⁴ Unlike transient thermo-reflectance, SSTR can be used to thermally characterize thick layers 2 to 500 μm thick (determined by spot size) and can measure thermal conductivities over three orders of magnitude, up to that of diamond (Fig. 5-3). It has recently been demonstrated that this technique can be used to determine how defects affect thermal performance. In addition, it can be used to characterize buried interfaces, which is of high importance for developing new thermal packaging approaches. For UWBG semiconductors, an additional challenge is to develop UV sources that can be absorbed in these materials to excite electrons with energies greater than the bandgap. This allows for the measurement of thermal properties by a thermo-reflectance technique without the need for a metal transducer layer, which adds inherent thermal resistance to the system and reduces sensitivity to buried interfaces.

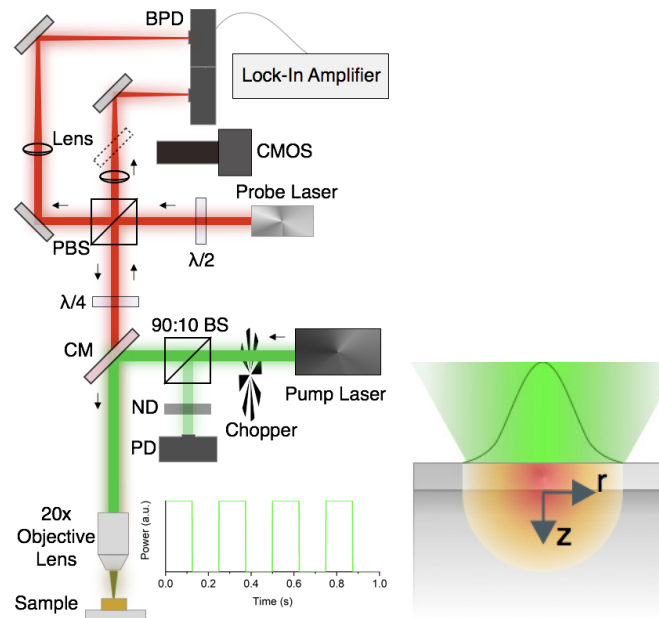


Fig. 5-3 (Left) Diagram of the SSTR instrumentation. (Right) Diagram of the spot-size, which can vary from 2 to 500 μm . The effect of a material interface can readily be measured when the spot size is significantly larger than the interface depth.

5.3 Magnetic Materials

5.3.1 Magnetics for High-Power Applications

The session was opened by Paul Ohodnicki of NETL, who pointed out that WBG and UWBG devices are creating new challenges and opportunities for passive power electronic components, including magnetics. Breakthrough magnetics research will require sustained and focused research and development efforts, and the identification and nurturing of qualified technical talent. Soft magnetic materials are what enable inductors, transformers, and electrical machines, and are critical for energy conversion. However, to enable UWBG semiconductors to achieve their promised high-power densities and switching frequencies, advanced soft magnetic materials must be developed. Excellent review articles covering recent progress in advanced soft magnetic materials have appeared recently.^{5,6}

Advanced soft magnetics have needs and opportunities that range from medium voltage (600 V to 69 kV) distribution power electronics and electric vehicle charging in the near term to high-speed, megawatt-scale rotating electrical machinery in the intermediate term, to high voltage and beyond (≥ 69 kV) for transmission power electronics in the long term. For all these applications, higher switching frequencies enable increases in power density and enormous reductions in the weight of equipment, such as going from 30 tons to 450 lb for a 2-MW power transformer. Such scaling is ultimately limited by efficiency and thermal constraints. While higher frequency enables smaller magnetic core volumes/areas, the material losses increase significantly at high frequencies.

The desired properties of a soft magnetic material include high saturation magnetizations B_s (enabling high power densities), low coercivities H_c (enabling low hysteretic losses), high resistivities r (enabling low eddy current losses), and low magnetostriction (enabling lower mechanical strain). For applications at the kilowatt scale and above, additional desired properties include high temperature stability and high thermal conductivity (enabling high thermal performance), and good mechanical properties and scalability of manufacturing processes (enabling large scale component fabrication).

An advanced magnetic material that is promising for high-frequency, high-power electronics is metal/amorphous nanocomposites (MANCs), essentially metal nanocrystals in a metallic glass matrix (Fig. 5-4). Precisely controlling the nanoscale microstructure enables one to pin grain boundaries, thereby reducing hysteresis. Nanocomposites with grains below a certain size (~ 20 to 30 nm) show dramatically lower losses⁷ (Fig. 5-5). High resistivity can also be obtained, dramatically lowering eddy current losses. Both thermal annealing and “strain

annealing” modify the grain structure to improve performance. Cobalt-based MANCs have shown particularly large responses to stress annealing, compared to Fe-based MANCs.⁸ These materials appear suitable for high-power electronics up to frequencies of a few tens of kilohertz. For higher frequencies, ferrites are the best option, but have significantly lower magnetic saturations. This is because the MANC electrical resistivity is still much lower than that of ferrites, yielding an unacceptable degree of eddy current heating at higher frequencies. New and better materials are still needed, especially above 100 kHz.

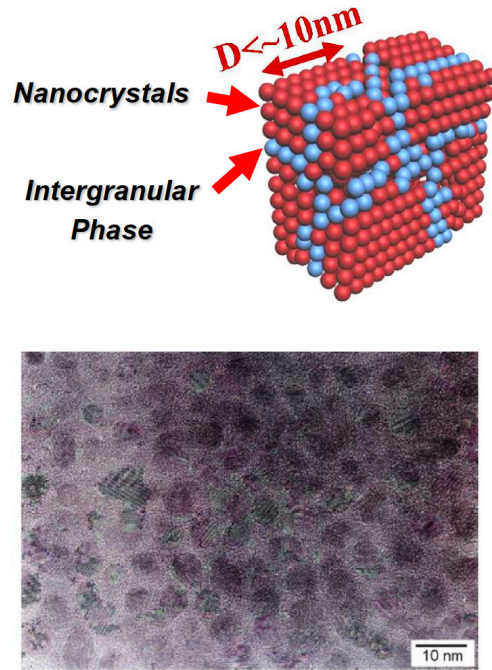


Fig. 5-4 Sketch (top) and electron micrograph (bottom) of a MANC, essentially comprising metallic nanoparticles embedded within a metallic glass matrix

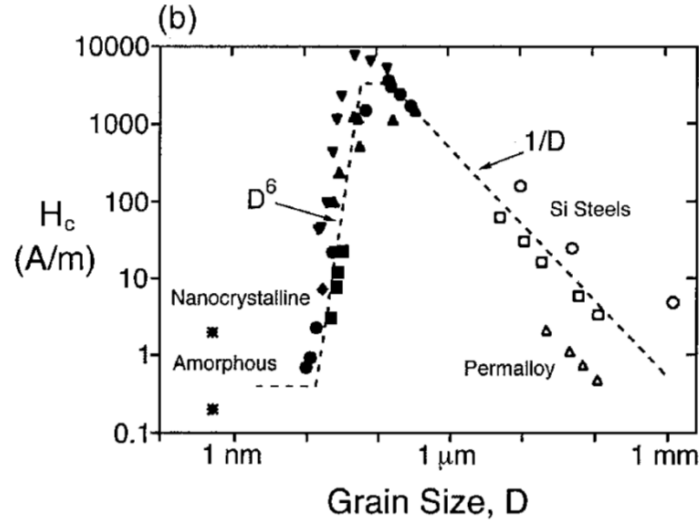


Fig. 5-5 Plot of coercivity H_c (the primary cause of hysteretic losses) vs. grain size for a variety of soft magnetic materials. When the grain size becomes smaller than a few tens of nanometers, the coercivity drops precipitously, minimizing hysteretic losses.⁷

A recent approach to fabricating magnetic cores is that of “permeability engineering”. With uniform permeability, a magnetic core typically has much larger flux density toward the center. Since losses typically increase superlinearly with flux density, this creates hot spots within the magnetic core and can lead to failure. However, by modulating the permeability of a ribbon or tape of core material, and then winding this ribbon around a spool to form the core, the permeability of the core can be varied. In this way, the density of magnetic flux can be engineered to be more constant throughout the core, enhancing its thermal robustness.⁹ Future directions for high-frequency inductors will include nanocomposite/ferrite hybrid designs to minimize flux leakage.

5.3.2 Magnetic Materials: Ferrite-Based Magnetics

Will Harris of Northeastern University then discussed magnetic materials for RF applications, for which the requirements are somewhat different. While saturation fields and power densities are not unimportant, the critical metric is operation at several tens of gigahertz. Higher frequencies require shifting to ferrite-type magnetic materials, and specifically certain specialized ferrites are capable of frequencies as high as tens or even a hundred gigahertz. A notable example is M-type hexaferrites, where barium/Sr is added to a ferrite crystal to break the symmetry and shift up the magnetic resonance frequency. This technique works, but requires a magnetic bias (an attached permanent magnet) to obtain desirable performance characteristics. This requirement is a major limitation, and a DARPA program in the area was unable to fully solve the issue. Recently, however, it has

been demonstrated that it is possible to self-bias the ferrite using crystal anisotropy, leading to the possibility of new innovations in the area.

An example application is a GaN-based transmit and receive module, including amplifier networks and passive components, operating at Ka band (26.5–40 GHz). Here one desires integration of magnetic and WBG/UWBG heterostructures in a next-generation system-on-wafer monolithic microwave integrated circuit to reduce parasitics. Out of the currently available magnetic materials, the high frequencies render only the ferrites suitable. Three different integration approaches are presently being explored. In the first, atomic layer deposition is used to deposit nucleation layers on WBG substrates (e.g., GaN or SiC) and PLD is subsequently used to deposit thin films of ferrite (e.g., M-type hexaferrites). A second approach is pick-and-place of ferrite elements onto the chip, while a third approach is wafer bonding between UWBG and ferrite wafers.

5.4 Dielectric Materials

5.4.1 Gate and Passivation Dielectrics

This session opened with a talk by Sarit Dhar of Auburn University on gate dielectrics for UWBGs. For a wide variety of UWBG devices, new dielectric materials are needed for passivation and as gate insulators. Examples include GaN HEMTs, SiC bipolar junction transistors (BJTs) and double-implanted MOSFETs (DMOSFETs), and Ga₂O₃ MOSFETs. Depending on the device properties that need to be achieved, the dielectric will require certain characteristics, such as high dielectric constant (for higher capacitance), low defect densities in the bulk (for low leakage at high electric fields), low interface state densities (for carrier confinement and gate control), adequate band offsets (for good charge transport characteristics), and stability and low interface scattering (for good stability and reliability). Requirements for a particular dielectric will be specific to the semiconductor material and the device architecture. Properties of the dielectric–semiconductor interfaces determine the device operation. High-K dielectrics will need to provide performance and reliability that is comparable to nitride silicon dioxide (SiO₂) on SiC. Successful dielectric deposition depends on the starting surface termination as well as the final interface chemistry. The community is currently engaged in an ongoing search for new materials using computational simulation of properties and development of deposition methods.

For SiC MOSFETs, the most common gate dielectric is SiO₂, with nitridation as the most widely accepted interface treatment. Nonetheless, there can remain a significant density of interface traps at the SiC/SiO₂ interface¹⁰ despite partial

passivation of those traps by nitridation.¹¹ This limits channel mobility, and improved UWBG dielectrics for WBG MISFETs remain a critical need.

Novel high-K dielectrics are one approach and are a current topic of ARL research. Attractive candidates include BeO and the fluorides CaF₂ and MgF₂ due to their unusually large bandgaps exceeding 9 eV. These can be deposited using ALD but require a carefully prepared interface. While Si has required a hydroxylated interface for high-quality ALD deposition, SiC benefits from hydrofluoric acid etching of thermal oxide to produce an O-terminated surface.¹² One approach for SiC gate dielectrics is ALD-deposited Al₂O₃ on top of a SiO_x transition layer. A recent study found a significant decrease in interface traps, but with significantly increased leakage currents.¹³ Investigations of ALD-deposited Al₂O₃ on Ga₂O₃ have similarly found a lower density of interface traps than that of SiO₂ on Ga₂O₃ but with larger dielectric leakage.¹⁴

5.4.2 Dielectric Materials: Dielectrics for Energy Storage

T Richard Jow from ARL presented on dielectrics for use in capacitors for energy storage at the circuit level. UWBG semiconductors will allow higher switching frequencies (from 20 kHz to potentially hundreds of megahertz), higher operating voltages (from 400 to 1200 V and higher), and higher junction temperatures (from 105 to 200 °C) for more efficient power conversion in power electronic applications. The needed capacitors in the power conversion circuits also must be improved to take advantages of these features.¹⁵ For high switching frequency operation, the capacitors are required to be small, low equivalent series resistance (ESR), low equivalent series inductance (ESL), and low loss with high dV/dt and high current handling capability. The capacitors are also required to operate at high voltages to match the high voltages of UWBG devices and at high temperatures so that the capacitors can be packaged closed to the hot semiconductors to reduce the ESL and cooling burden. As such, the dielectric materials, the key component of the capacitive energy storage in the capacitors, also need to be improved over the current state-of-the-art biaxially oriented propylene (BOPP). High-temperature dielectric thin films with low dissipation factor (DF), high breakdown strength, high dV/dt, and high insulation resistance across a temperature range of -40 to 200 °C are desired. The design of electrodes for the dielectric film impacts the current-carrying capability, ESR, breakdown strength, and operation life of the capacitor.

Capacitors for pulsed power applications, especially for fast pulses on the timescale of microseconds at higher rep rates, also require dielectric films with properties similar to those required for power conversion using UWBG-based power electronic circuits. For millisecond-timescale discharge capacitors, dielectric films

using metallized film electrodes can handle the required currents. High-temperature dielectrics and low-loss materials are desired for high rep rate operation.

The challenge is whether the desired dielectric films exist that can take advantage of the UWBG semiconductors for meeting power conversion or pulsed power needs. For high temperature, lower-voltage applications and smaller sizes, ceramic capacitors seem ideal. But the high DF, low breakdown strength, and lower capacitance at higher voltage make ceramic capacitors less ideal for high-temperature, high-voltage, and high-frequency operations especially when a large capacitance capacitor is required. A comparison of a Gore high-temperature polytetrafluoroethylene (PTFE) film capacitor with an X7R ceramic capacitor is a good example.¹⁶

Polymer film dielectrics have the advantages of low DF, high breakdown strength, and generally higher insulation resistance than ceramic dielectrics. However, finding an ideal high-temperature polymer film that is as good as BOPP but operates at higher temperatures (e.g., from 125 to 200 °C) is a challenge. Recently reported Gore PTFE film¹⁷ exhibited higher breakdown strength than BOPP, polyether ether ketone, and polyethylene naphthalate (PEN) in a temperature range of 25 to 200 °C. At 150 °C, the Gore PTFE has a breakdown strength of 570 V/ μm while PEN has only 420 V/ μm . PTFE films made of different processes often reported lower breakdown strength than Gore films. This is one example illustrating that processing greatly impacts the performance of the film.

Synthesizing the dielectric film with the desired properties is only the first step of several. These include the processing of films to achieve the correct morphology, crystallinity, and purity, as well as a large area with uniform thickness as required for the application. The steps needed beyond achieving good films include designing electrodes that allow for high current carrying capability, ESR, and breakdown strength. Long life and high-voltage operation also rely on the self-healing ability of the dielectric film and incorporating the electrode as an integral part of the system. The capacitor assembly and package are the final step. All the new dielectric films need to go through these steps to validate their commercial viability for practical use. The weakening of the chemical industrial base and insufficient funding in the United States are gaps that need to be addressed for improved dielectric materials development and processing.

5.5 Conclusions

To fully realize the advantages of UWBG semiconductors at the system level, several classes of complementary materials must be concurrently advanced. The higher power densities of UWBGs will require improved thermal materials and

interface designs, calling for a co-design approach. Understanding heat generation and flow profiles is aided by in-situ Raman thermometry, steady-state thermoreflectance imaging, and IR thermography. Strategies for dealing with heating issues in HEMT devices include flip-chip strategies and applying cooling from the top-side using jet-impingement of a dielectric fluid.

The higher frequencies of active UWBG power devices will require new passive power electronic components. Advanced soft magnetic materials are required to enable UWBG semiconductors to achieve their promised high power densities and switching frequencies, enabling enormous reductions in the size and weight of inductors, transformers, and electrical machines. Promising advanced soft magnetic materials with high saturation magnetization at higher frequencies, low coercivity, and/or high electrical resistivities include metal/amorphous nanocomposites. “Permeability engineering” modulates the permeability of a magnetic core to achieve more uniform magnetic flux, enhancing thermal robustness. For RF applications, operation at several tens of gigahertz requires the use of ferrite-type materials, for which different on wafer integration approaches are being explored.

New dielectric materials are needed as passivation layers and gate dielectrics for UWBG devices, and must have high dielectric constants, low bulk defect and interface state densities, adequate band offsets, and material stability. Novel high-K dielectrics such as BeO and the fluorides CaF₂ and MgF₂ are currently being investigated at ARL, due to their unusually large bandgaps exceeding 9 eV. ALD-deposited Al₂O₃ is also being investigated for use on SiC and Ga₂O₃, but suffers from leakage currents.

Different dielectric materials are also needed for use in capacitors for energy storage at the circuit level. UWBG semiconductors will necessitate higher frequencies (potentially 100’s of MHz), higher voltages (400–1200 V or more) and higher temperatures (to 200 °C) for more efficient power conversion. Different capacitor materials have different suitability depending on how conditions (high frequency, voltage, temperature) are combined with the current state of the art being BOPP. Film synthesis and processing to achieve the correct morphology, crystallinity, and purity over a large area of uniform thickness, and incorporating the electrode as an integral part of the device are critical for polymer film dielectrics.

5.6 References

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6. Applications

6.1 Applications of AlGaN UV Optoelectronics

Author: N Johnson (PARC)

The following talk was presented by Mike Wraback (ARL): “AlGaN UV optoelectronics”.

The last session of the workshop emphasized applications of UWBG materials and devices. The session was initiated with a presentation by Michael Wraback of ARL on “Applications of AlGaN UV optoelectronics”.

Needs and opportunities where AlGaN UV optoelectronics can impact the DOD mission include reducing the size, cost, and durability of photo-multiplier tubes (PMTs), UV lasers, and UV lamps. As highlighted in Fig. 6-1, such continuing improvements will have impact on many critical technologies for the Army, which include bioagent detection based on light-induced fluorescence, water purification, UV laser detection and ranging, UV imaging, and UV covert communications. These enhancements have the additional benefit of reducing the logistical burden of the Warfighter.

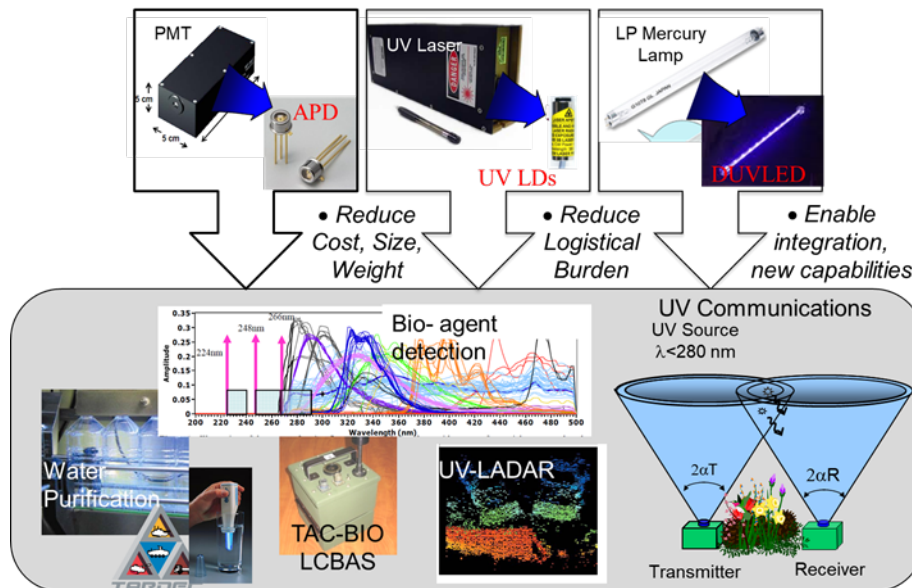


Fig. 6-1 DOD optoelectronic needs: the opportunity

The following is a list of specific applications that will benefit from continuing advancement of sources and detectors in the UV, with target values for key performance metrics:

- Low-cost, low-size, weight, and power (SWaP) biodetection:
 - 265–280 nm LED or laser diode, >50 mW continuous wave (CW), 10% wall plug efficiency (WPE)
 - 220–225 nm LED or laser diode, >20 mW CW, 10% WPE
 - Avalanche photodiodes (APDs) for 220–365 nm with >30% single photon detection efficiency (SPDE), 10-mm² active area, and dark count rate (DCR) <100 Hz/mm²
- Chem/bio/explosives identification
 - 230–250 nm single mode, single frequency laser, >1W CW, 10% WPE
 - APD array for 230–265 nm with >30% SPDE, and DCR <100 Hz/mm²
- Water purification:
 - 265–280 nm LEDs, >100 mW, 30% WPE
- Chemical/total organic carbon (TOC) decontamination:
 - 185–240 nm incoherent source, higher power (>0.5 W) for decontamination, higher photon energy for TOC measurement
- Non-line-of-sight communications:
 - 240–270 nm LEDs, >100 mW, >20% WPE
 - APDs for 240–280 nm with >30% SPDE, 10-mm² active area, and DCR <100 Hz/mm²
- Radioisotope power sources (beta(photo)voltaics)
 - 250–280 nm high conversion efficiency (>50%, >4 V_{oc}) photovoltaics
- Low-cost, low-SWaP photolithography
 - Sub-200-nm single mode, single frequency laser, >1 W CW, 10% WPE
- Quantum information processing:
 - single-mode, single-frequency laser at 369.5, 313, 280, and 215 nm
 - low power approximately 1 mW, approximately 20-MHz linewidth, vertical cavity surface emitting laser (VCSEL) or

VCSEL with an external laser resonator, optical cycling, and fluorescence detection

- medium power approximately 10 s of mW, photoionization
- high power (~1 W) or mode locked, Raman transitions for gate operations or entanglement
- AlN photonic integrated circuits (ICs)
- APDs with >80% SPDE and DCR <10 Hz/mm²

6.2 High-Power Electronic Applications

Author: D Pavlidis (Florida International University [FIU])

The following were presented:

- Lynn Petersen (Office of Naval Research [ONR]): “Applications of wide bandgap semiconductors for Navy power and energy needs”
- Don Dorsey (AFRL): “Ga₂O₃ high-power and RF electronic applications”
- Isik Kizilyalli (Advanced Research Projects Agency–Energy [ARPA-E]): “UWBG semiconductors of interest to ARPA-E”

6.2.1 Introduction

UWBG devices are of major interest considering that electricity is 40% of US energy consumption.^{1,2} It is predicted that by 2030, 80% of electricity could flow through power converters.^{1,2} UWBG devices could therefore play a major role in their production. Electricity is in fact used in various sectors such as lighting (12%), motors (50%), HVAC (16%), and IT (14%), where such components could be introduced. Both GaN and SiC technologies are expected to make a major contribution in this area by demonstrating devices and circuits that operate up to 20 kV. BN and diamond could also be of interest in applications such as neutron detectors.³

An important DOD application of UWBG semiconductors is the Navy’s electric warship. The USS *Zumwalt* guided missile destroyer (DDG-1000) was the first integrated power system-based system that contains medium voltage alternating current (MVAC) generation, rectification to a 1000-VDC integrated fight through power distribution and inversion to 450 VAC for ship service and hotel loads. Compact power systems are required to enable future payloads (Fig. 6-2). The power converters have Si devices. The electric warship of the future will need to expand on this previous success to include ES to facilitate an integrated power and

energy system (IPES) (Fig. 6-3) to facilitate the incorporation of high-power, pulsed duty mission loads.

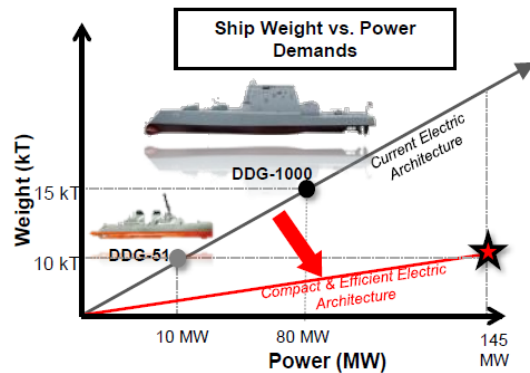


Fig. 6-2 Ship weight vs. power and requirements for future compact and efficient electric architectures

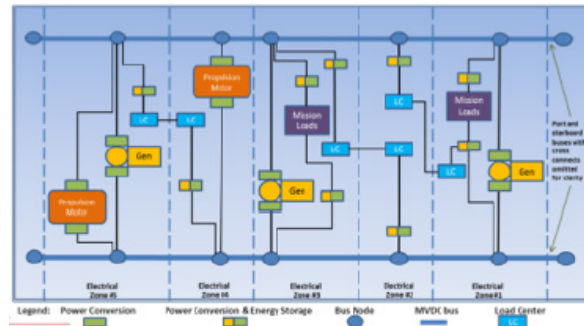


Fig. 6-3 IPES

Further, development and implementation of advanced power control systems to work with the ES and distribution systems will be required. Efforts are currently being made in this area as evidenced by ONR's investment in both 6.1 basic and 6.2 applied research and future naval capabilities. Shipboard power conversion applications include AC–DC and AC–AC converters, electric propulsion drives, electromagnetic aircraft launching and recovery systems, point-of-load power converters for distribution systems, auxiliary motors and drives, high-energy weapon systems, pulsed-power systems, and ES systems. The power converters of the future will transition from Si to SiC to enhance power density and efficiency.

A new addition to the UWBG family is Ga₂O₃ and is found to be promising for high-power and RF electronic applications. Semiconductors of this type are expected to dramatically improve military aircraft power systems and address power density challenges as requirements continue to trend upward toward 1 MW and beyond. Power management systems are expected to simplify in this way by

lower cost and by being more sustainable. β -Ga₂O₃ is expected to have impact in the low-medium voltage range (<1.2 kV) to cover military aircraft generator voltages and possibly battery-powered unmanned systems. The high electric-field strength allows aggressive scaling to enable high-speed switching. Compact voltage down-conversion and improved power efficiency are expected with this material. RF applications include the development of class E amplifiers and integration with GaN is expected to improve RF operation by on-chip power management for RF circuits.

6.2.2 Applications Considerations and Recent Progress

Consideration of SiC device characteristics suggests that conventional unipolar devices are limited to low current densities of approximately 20 A/cm² due to large conduction losses (Fig. 6-4). The same occurs in conventional bipolar devices where the WBG and resulting knee voltage lead also to large conduction losses that limit them to low current densities. Super-junction or charge-balanced devices could provide a solution by offering improved current densities at megavolts. Consideration of GaN-based approaches suggests that 10-kV operation is feasible.⁴

Advanced circuit topologies with WBG semiconductor materials are being explored to realize efficiency gains both directly and indirectly in electric power conversion. These are expected to result in efficient DC–DC, DC–AC, and AC–DC converters (≥ 10 kW), small size, low weight, reliable—power density of more than 100 W/inch³ with important applications in power supplies, data centers, and motor drives.^{4,5}

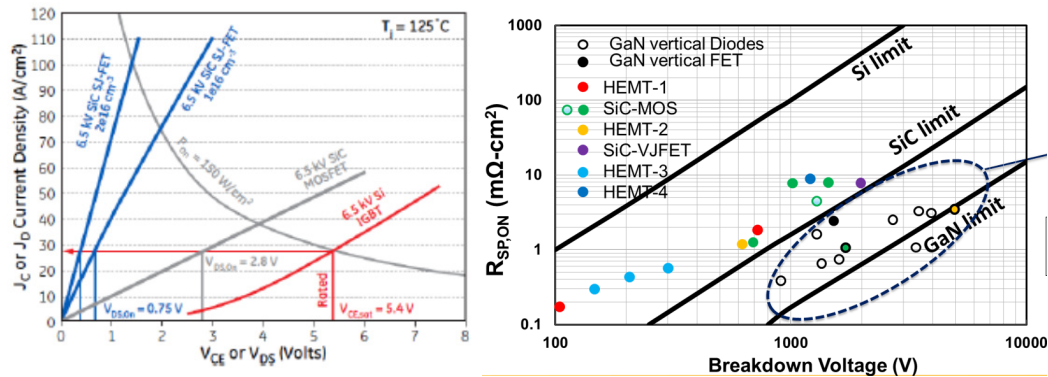


Fig. 6-4 SiC device options scaling to medium voltage (left) and WBG semiconductors allowing more than 5 kV

Packaging of UWBG semiconductors imposes additional challenges due to parasitics. Studies show that traditional chips-package-circuit separation will not work in the future and a holistic approach with no explicit boundaries is required. Three-dimensional integration will provide a solution to this problem by shorter,

low inductive connections and commutation cells. Major challenges are, however, faced for high current (100 A), voltage (1200 V), and temperature ($>150\text{ }^{\circ}\text{C}$).

Electromagnetic interference (EMI) is an additional challenge faced by UWBG-based applications. There are several sources of increased EMI challenges in UWBG devices and circuits such as an intrinsically faster dV/dt and di/dt , which lead to increased high-frequency harmonics. As a result, SiC converters present 30 to 300 times greater harmonic amplitude than comparable Si systems (Fig. 6-5). One has also to keep in mind that EMI management corresponds to an additional expense and constitutes 10%–40% of current system cost. System lockups and hardware failure can result from EMI-related issues.

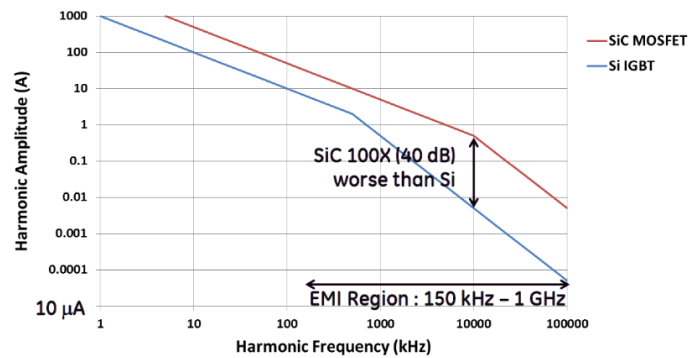


Fig. 6-5 SiC greater harmonic amplitude in SiC converters vs. comparable Si systems

Examples of circuits of interest for UWBG applications include flying capacitor converters, solid-state circuit breakers, direct AC–AC matrix converters, current-source inverters, soft-switching converters, solid-state transformers, universal converters, SiC photonic device-based converters, GaN gate driver ICs, and transistor-less DC–DC converters.

Medium voltage direct current (MVDC) markets require the development of novel DC circuit breaker technologies operating in the range of 1.5–100 kV. These will have potential applications in grid resiliency, renewable and storage interconnection, electric aviation, electric ships, and oil as well as gas.⁶ MVDC distribution can save 1.1 quads of energy per year, reduce US emissions by 3% via electrification of transportation, and lower offshore oil and gas rig costs by 5%. High-speed, low-loss MVDC circuit breakers will enable MVDC markets by providing circuit and electrical equipment protection (e.g., power converters, power lines).

Diamond is another promising UWBG technology.⁷ Various devices such as Schottky diodes but also transistors have been explored with it (Fig. 6-6). Substrate development resulted in diamond substrates with dislocation defect densities of low

10^3 cm^{-2} . More than 1000-V breakdown has been achieved corresponding to a field strength of approximately 3–4 MV/cm). A current density of 100–900 A/cm² was demonstrated for diameters of approximately 150–500 μm .

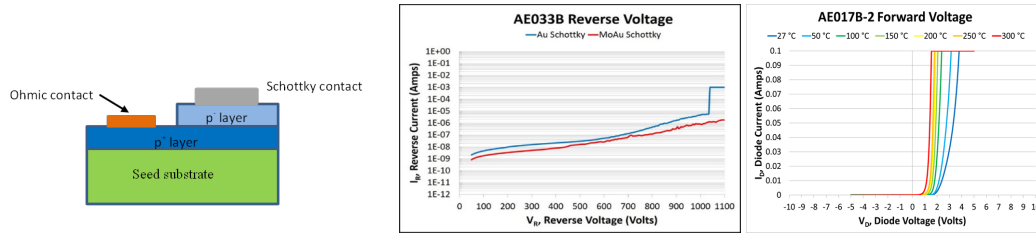


Fig. 6-6 Diamond Schottky diodes and electrical characteristics

Both n- and p-type conductivity in (100) and (111) diamond layers has been achieved using phosphorus and boron (PN), and PN diodes have been studied using such materials. The devices showed a turn on voltage of approximately 4 V with light emission indicating bipolar transport and the breakdown field was approximately 3.9 MV/cm. Diamond BJT devices have also been proposed but not demonstrated. Diamond PiN neutron detectors are of interest and present the fastest response among known detector materials while maintaining performance at high temperatures. Their intrinsic electric field of approximately 1 V/ μm allows for compact designs in medical, space, and energy applications. They are nearly insensitive to gamma rays, allowing the effects of radiation damage to be minimized.

Compact power systems are required to enable future payloads and WBG semiconductors promise to offer solutions to it using III-nitrides. GaN has, for example, a 10 times higher BFOM than SiC and vertical device architecture is enabled by large-area, high-quality, truly bulk substrates that are now available. However, significant materials challenges are faced to realize high-performance devices that include selective-area, controlled p-type doping and low background doping for drift layers.^{4,8}

A high power density is required for MV converters. HVDC remote suburban areas require for example 0.01 MW/m³, while future naval MVAC and MVDC systems require greater than 1 MW/m³. Other applications that require high density power include commercial marine systems, industrial drives, and wind inverters. Vertical GaN offers the possibility of low ON-resistance and reduced SWaP (Fig. 6-7).

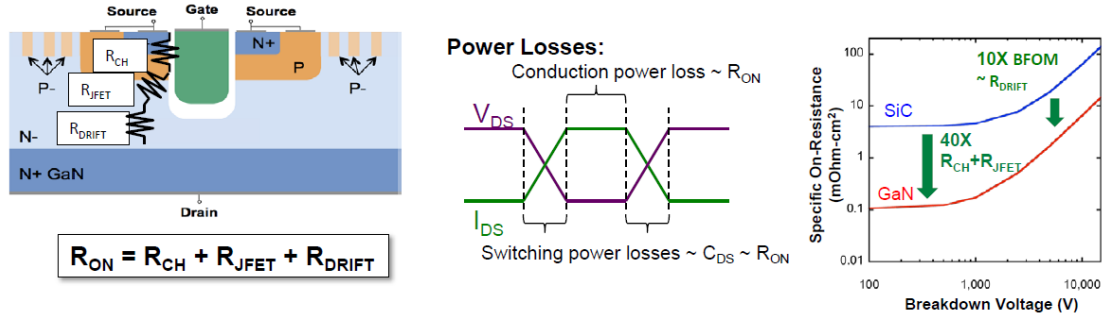


Fig. 6-7 Vertical GaN for low ON-resistance and reduced SWaP

Conduction power loss is proportional to device R_{on} , which is determined by several components ($R_{ON} = R_{CH} + R_{JFET} + R_{DRIFT}$) and is lower in GaN than SiC, as shown by studies of the specific ON-resistance dependence on breakdown voltage. A lower ON-resistance leads to lower losses, higher frequency of operation and smaller passive components. For example, within the 1-kV breakdown range, $R_{CH} + R_{JFET}$ is 40 times smaller in GaN than SiC. Least-replaceable units (LRUs) are modular components of the ship designed to be replaced quickly at an operating location and can benefit from UWBG technology. (Fig. 6-8).

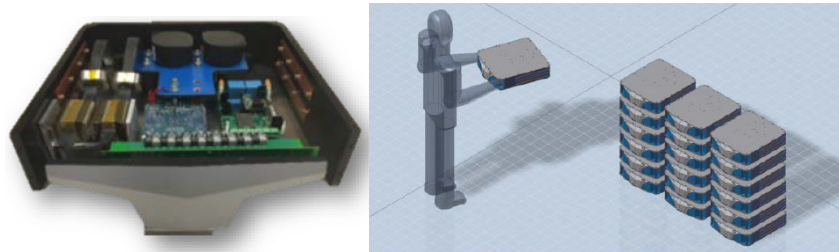


Fig. 6-8 LRU and the PEBB 1000 vision

Shipboard PEBBs, namely, the PEBB 1000 (two variants developed). First, General Electric built and demonstrated a PEBB 1000 using commercially available 1.7-kV SiC devices, included a high-frequency transformer, operated at a switching frequency of 165 kHz, power rating of 135 kW, and 99.2% efficiency. A modified version of PEBB 1000 LRUs now have the ONR multi-function hybrid energy storage module built by GE and have transitioned to the GE wind turbine industry. Second, the Virginia Polytechnic Institute and State University (Virginia Tech) built a PEBB 1000 based on 1.7-kV SiC devices. It does not have a high-frequency transformer. It is rated at 100-kHz and 70-kW power. As of 2019, the Virginia Tech PEBB1000 (Fig. 6-9) consisted of an H-bridge with integrated filter, bottom and top heat spreader surfaces, and simplified electrical, mechanical, and thermal connections.

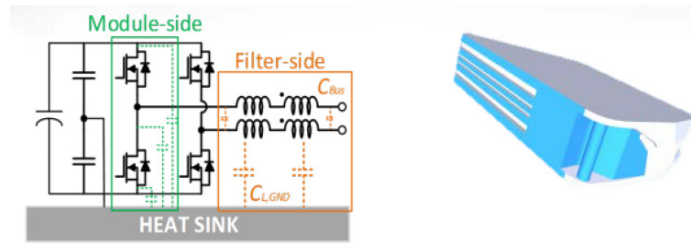


Fig. 6-9 Virginia Tech PEBB 1000 with integrated filter, bottom/top heat spreader, and simplified electrical/thermal connection

Future developments will include transformer input and output H-bridges with integrated transformer and internal water cooling. Future PEBB LRUs would require all four H-bridges, no external water connectors, and simplified electrical and mechanical connections, and need to be Sailor-safe and allow hassle-free installation and maintenance

These can take advantage of UWBG technology, which allows among other things 100 kHz or greater switching, field-programmable gate arrays for high-speed control and intelligent power modules. Moreover, high-frequency magnetics and highly integrated PEBB-based converters will be required to successfully realize the desired power-electronic power distribution system concept.

The goal for PEBB 6000 includes the development and demonstration of a full-bridge, self-contained, SiC-based LRU rated at 1 MW, 6 kV, and 40 kHz with a power density of 10MW/m^3 , 99% efficiency, zero conducted EMI emissions, a 30-kV partial discharge inception voltage, and 0-V enclosure potential. This will require evaluation of power quality, switching performance, efficiency, EMI conducted and radiated emissions and compliance, partial discharge (PD) characteristics, and a thermal design of the PEBB units.

It is important to note that although past power electronic goals aimed at the smallest, lightest, and lowest-cost components, present objectives aim at more control, more functions, more integration (physical and functional), more flexibility, and commonality. Science and technology is required to focus on technology gaps that include among other thermal management, insulation, high-power/frequency magnetics ($>1\text{ MW}/>100\text{ kHz}$), UWBG semiconductors, and PEBB module integration and packaging.

Power electronic control sets up new challenges compared with classical control. These include decoupling source and load impedances, dynamic impedance matching, and decision-making at the switch level (intelligent switches).

β -Ga₂O₃ presents improved RF and power switching metrics compared with other WBG materials.⁹ For example, the BFOM ($\mu\epsilon E_c^3$) that characterizes power switching (minimized conduction losses) is 2870 for β -Ga₂O₃ versus 870 for GaN (Fig. 6-10). Also, the chip area figure of merit (HCAFOM) ($\epsilon\mu^{0.5}E_c^2$) that provides information on manufacturing cost (chip area, power density) is 255 for β -Ga₂O₃ versus 85 for GaN.

	Si	GaAs	4H-SiC	GaN	β -Ga ₂ O ₃	Diamond	AlN
E_g (eV)	1.1	1.4	3.3	3.4	4.9	5.5	6.2
μ (cm ² /V·s)	1400	8000	1000	1200	250	2000	850
E_c (MV/cm)	0.3	0.4	2.5	3.3	8	10	15.4
ϵ_{REL}	11.8	12.9	9.7	9	10	5.5	8.5
v_{SAT} (10 ⁷ cm/s)	1.0	1.2	2.0	2.5	1.1	1.0	2.0
λ (W/m·K)	150	50	370	130	10, 30	2000	340
BFOM ($\mu\epsilon E_c^3$)	1	15	340	870	2870	24661	59160
JFOM ($v_{SAT}E_c$)	1	2	17	28	29	33	103
HMFOM ($E_c\mu^{0.5}$)	1	3	7	10	11	40	40
HCAFOM ($\epsilon\mu^{0.5}E_c^2$)	1	5	48	85	255	619	1479
HTFOM ($\lambda\epsilon^{-1}E_c^{-1}$)	1	0.23	0.36	0.10	0.01	0.86	0.06

Fig. 6-10 RF and power switching metrics

β -Ga₂O₃ power devices have been laterally scaled in terms of dimensions to achieve low-loss, high-efficiency power (Fig. 6-11). Studies focused on gate-to-source resistance that can be reduced with self-aligned contacts, gate-to-drain resistance that can be optimized to fit the estimated drift region (W_D), and gate contact can be made smaller (L_G) to reduce the channel resistance and gate charge (Q_G).

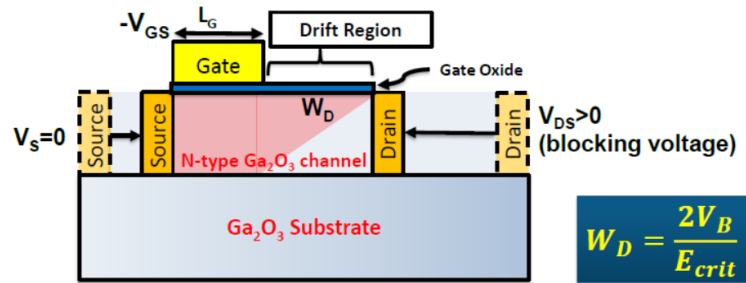


Fig. 6-11 Lateral Ga₂O₃ MOSFET and device optimization

Mobility versus carrier concentration studies of epitaxial β -Ga₂O₃ materials suggest that low-voltage performance may be better than expected and there is significant room for improvement at low doping range. Without implant, ohmic contacts have been difficult to form ($70 \Omega\cdot\text{mm} < RC < 3 \Omega\cdot\text{mm}$). However, metalorganic vapor phase epitaxy epitaxial n++ ohmic contact layers achieved $RC < 1 \Omega\cdot\text{mm}$ while PLD n++ ohmic contacts achieved $RC < 0.2 \Omega\cdot\text{mm}$. Overall, the studies showed that as-grown and regrown contact layers are viable. Without optimization, the

Si-implant sheet resistance achieved was less than 200 ohm/sq using a short rapid thermal annealing (RTA) process of 900 °C in N₂ for 2 min for MOCVD and MBE Ga₂O₃ samples.

First-generation β -Ga₂O₃ device fabrication at AFRL consisted of mesa dry etch, ohmic metal followed by RTA, ALD Al₂O₃ dielectric, removal of ALD in selected areas over the ohmics, and gate-pad metal deposition. These processes led to a record-high $E_{crit} > 3.8$ MV/cm and record-high current density of I_{DSat} (at $V_{GS} = 4$ V) = 478 mA/mm. More recent generations of device technology involved boron trichloride (BCl₃) inductively coupled plasma (ICP) mesa etch, Ti/Al/nickel/Au ohmics, BCl₃ ICP epitaxial cap etch, PECVD SiO₂, carbon tetrafluoride reactive-ion etching and BCl₃ ICP recess, ALD gate dielectric, clearing ohmic contacts, and interconnect and gate deposition (Fig. 6-12).

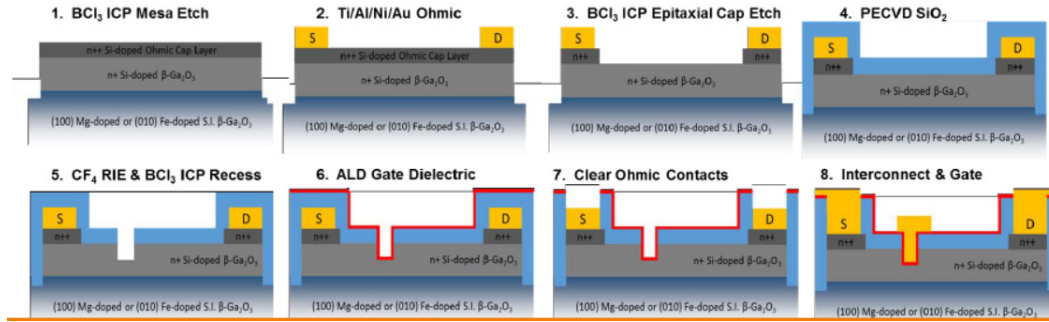


Fig. 6-12 Second-generation β -Ga₂O₃ FETs at AFRL (2017–2018)

These led in the demonstration of recessed-gate E-mode β -Ga₂O₃ MOSFETs with I_{max} of 40 mA/mm, I_{on}/I_{off} of 10^9 , $SS < 200$ mV/dec, and V_{BK} of 200 V for $L_{SD} = 3$ μ m. A dynamic switch loss analysis $R_{ON} \cdot Q_G$ showed that R_s , R_D , and R_{CH} all benefit from dielectric/Ga₂O₃ interface depletion optimization. Moreover, with feasible optimization, switch losses are competitive with the best reported GaN.

Some promising progress has also been made in terms of RF Ga₂O₃ devices. Process enhancement applied to β -Ga₂O₃ RF devices permitted improvements in $R_c < 10$ X, $R_{SH} < 2$ X, $G_m > 2$ X, and $\mu > 5$ X. Early small-signal results for $L_G \sim 0.7$ μ m, $W = 100$ μ m for such devices showed MSG/MAG > 10 dB at $f > 1$ GHz, $R_c \sim 3$ $\Omega \cdot$ mm, $R_{sh} \sim 5$ k Ω/γ , and $\mu \sim 100$ cm²/V·s. Further optimization with a thin-channel MOSFET, a 65-nm Si:Ga₂O₃ epilayer, 25-nm Al₂O₃ gate oxide, $\mu = 90$ cm²/Vs led in record high f_{max} of 17.1 GHz for Ga₂O₃ FETs (Fig. 6-13). Pulsed load-pull characterization showed $P_{out} = 0.25$ W/mm and PAE = 15% at 1 GHz under class AB operation and a $P_{OUT-MAX}$ of 530 mW/mm was obtained. By replacing the T-gate with a self-aligned gate (SAG) MOSFET, parasitic access resistance reduced with increased $P_{out} = 730$ mW/mm and approximately 23% PAE under 1-GHz pulsed RF power conditions.

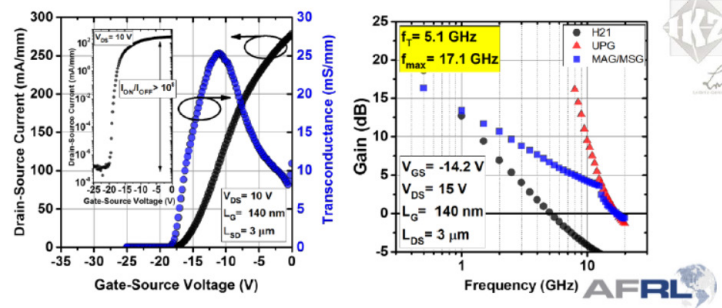


Fig. 6-13 DC and high-frequency characteristics of a third-generation device: thin-channel β -Ga₂O₃ FETs (2018)

Thermal studies were also conducted and thermal modeling for the same FET with $L_{SD} = 3$ μ m and 380 V/ μ m E_C run at open channel with $V_{DD} = 40$ V showed a thermal resistance without topside thermal dissipation design of 200 and 22 K/W with a topside solution. Flip-chip bonding with approximately 5- μ m-thick electroplated contacts on SiC and a Ga₂O₃ chiplet was explored for top-side heat extraction.

Future developments (Fig. 6-14) will address MBE-grown layers, heterostructure designs, removal of parasitic losses by scaling, field management with implant and field plate, and thermal engineering through top-side heat extraction.

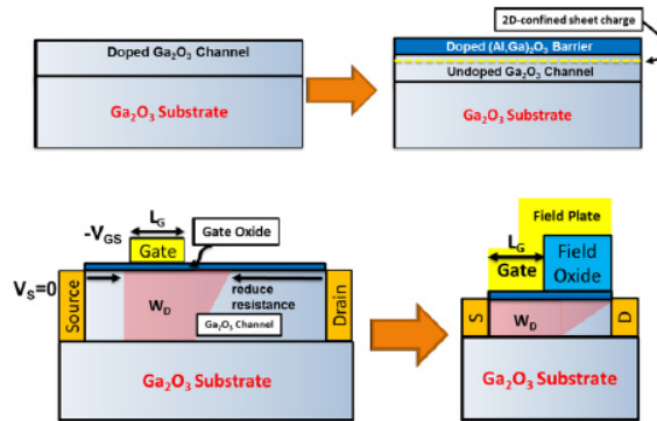


Fig. 6-14 Future developments for improved Ga₂O₃ device performance ("4th Gen" β -Ga₂O₃ FETs at AFRL [2019])

6.2.3 Conclusions

Super-junction or charge-balanced devices could offer improved current densities at a megavolt. Consideration of GaN-based approaches suggests that 10-kV operation is feasible. Advanced circuit topologies with WBG semiconductor materials are expected to result in efficient DC-DC, DC-AC and AC-DC converters (≥ 10 kW)—small size, low weight, reliable—power density of more

than 100 W/inch³ with important applications in power supplies, data centers, and motor drives. Three-dimensional integration will provide a solution to packaging UWBG semiconductors by shorter, low inductive connections and commutation cells. EMI is particularly important to consider in UWBG devices and circuits due to increased high-frequency harmonics. Applications in grid resiliency, renewable and storage interconnection, electric aviation, and electric ships will profit from the availability of novel DC circuit breaker technologies operating in the range of 1.5–100 kV. Devices such as Schottky diodes but also transistors have been explored with diamond and more than 1000-V breakdown has been achieved while a current density of 100–900 A/cm² was demonstrated.

WBG semiconductors such as III-nitrides promise to offer a solution to the realization of compact power systems required to enable future payloads. Vertical GaN offers the possibility of low ON-resistance and reduced SWaP. Conduction power loss is proportional to device R_{on} and is lower in GaN than SiC leading in lower losses, higher frequency of operation and smaller passive components. Future PEBBs LRUs will require four H-bridges, no external water connectors, and simplified electrical and mechanical connections, and can take advantage of UWBG technology. There is great need for focusing on thermal management, insulation, high-power/frequency magnetics (>1 MW/>100 kHz), UWBG semiconductors and PEBB module integration and packaging. Science and technology investment opportunities include thermal management, insulation, high-power/frequency magnetics (>1 MW/>100 kHz), UWBG semiconductors, and PEBB module integration and packaging.

β -Ga₂O₃ presents improved RF and power switching metrics compared with other WBG materials. It also presents a larger than GaN HCAFOM ($\epsilon\mu^{0.5}E_c^2$) that translates into lower manufacturing cost. Extensive studies have been conducted on β -Ga₂O₃ power devices to laterally scale them and achieve low-loss, high-efficiency power. E-mode β -Ga₂O₃ MOSFETs have been demonstrated and optimization can lead in switch losses competitive with the best-reported GaN results. Promising progress has also been made on RF Ga₂O₃ devices that demonstrated record high f_{max} of 17.1 GHz, as well as $P_{out} = 0.25$ W/mm and PAE = 15% at 1 GHz under class AB operation and a $P_{OUT-MAX}$ of 530 mW/mm. Future device performance will benefit from MBE-grown layers, heterostructure designs, removal of parasitic losses by scaling, field management with implant and field plate, and thermal engineering.

Some of the specific needs of the Navy are compact power systems are required to enable future payloads in DOD applications such as the Navy's electric warships. As the power demand increases, the ship weight increases very fast with the currently available electric architectures. The weight of the Navy's electric warship.

DDG-1000 with 80-MW power is expected to be reduced from 15 kT to about 8 kT by replacing the current electric architectures with compact and efficient electric ones. Shipboard power conversion applications include AC–DC and AC–AC converters, electric propulsion drives, electromagnetic aircraft launching and recovery systems, point-of-load power converters for distribution systems, auxiliary motors and drives, high-energy weapon systems, pulsed-power systems, and ES systems. The power converters of the future will transition from Si to SiC to enhance power density and efficiency. UWBG materials, devices, and modules are again expected to play an important role in DOD applications.

One of the important projects for the Air Force is the new and promising UWBG semiconductor, Ga_2O_3 , that could be used for high-power and RF electronic applications. It is expected to dramatically improve military aircraft power systems and address power density challenges as requirements continue to trend upward toward 1 MW and beyond. Power management systems are expected to simplify in this way by lower cost and by being more sustainable. $\beta\text{-Ga}_2\text{O}_3$ is expected to have impact in the low-medium voltage range (<1.2 kV) to cover military aircraft generator voltages and possibly battery-powered unmanned systems. RF amplifier applications include the development of class E amplifiers and integration with GaN to improve RF operation by on-chip power management for RF circuits.

UWBG semiconductors of major interest to ARPA-E for commercial applications are the development of components for power converters and devices. This is particularly interesting considering that electricity is 40% of US energy consumption, and it is predicted that by 2030, that 80% of electricity could flow through power converters. GaN and SiC technologies are expected to make a major contribution in this area through devices and circuits that operate up to 20 kV. BN and diamond devices have the potential to operate at higher voltages. These materials could also be used as neutron detectors.

6.2.4 References

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6.3 High Operating Temperature Sensors and Sensor Systems

Author: K Jones (ARL)

The talk was presented by Ben Griffin (DARPA): “High operating temperature sensors and electronics”.

6.3.1 Introduction

The primary attractions of piezoelectric devices are that the materials they are made of are stable, and devices fabricated from them can operate at high temperatures, are more radiation hard than traditional semiconductor devices, and are insensitive to EMI. Semiconductors such as AlN and ceramics such as langasite (La₃Ga₃SiO₁₄, LGS) have melting points much in excess of 1000 °C and their electrical resistivity at 1000 °C is very large. Devices made from the materials are more radiation hard both because it is more difficult to create point defects that are electrically active and their operation is less strongly affected by the creation of the point defects.

Like semiconductors, there are individual piezoelectric devices, such as those used to sense pressure changes in the chambers of turbine engines used in airplanes, as

shown in Fig. 6-15. Ultrasonic transducers can be used to monitor the pressure by measuring the change in the charge on the piezoelectric element. The change in pressure is a good indicator of how well the system is operating. A drop in pressure, especially one that is sudden, indicates that the system is operating below par. The transducers must be able to function at temperatures as high as 1250 °C. The obvious benefit of being able to continuously monitor operation enables the plane to operate more efficiently, so it can fly farther on the same amount of fuel. Times between routine maintenance could be longer, which could reduce costs. This monitoring procedure could also prevent a flame out by detecting the precursors such as a characteristic drop in pressure before the flame out would occur and take preventative actions before it happens. Similar monitoring could be done for internal-combustion engines, and the challenges would be fewer since they operate at a lower temperature: 300–1000 °C.

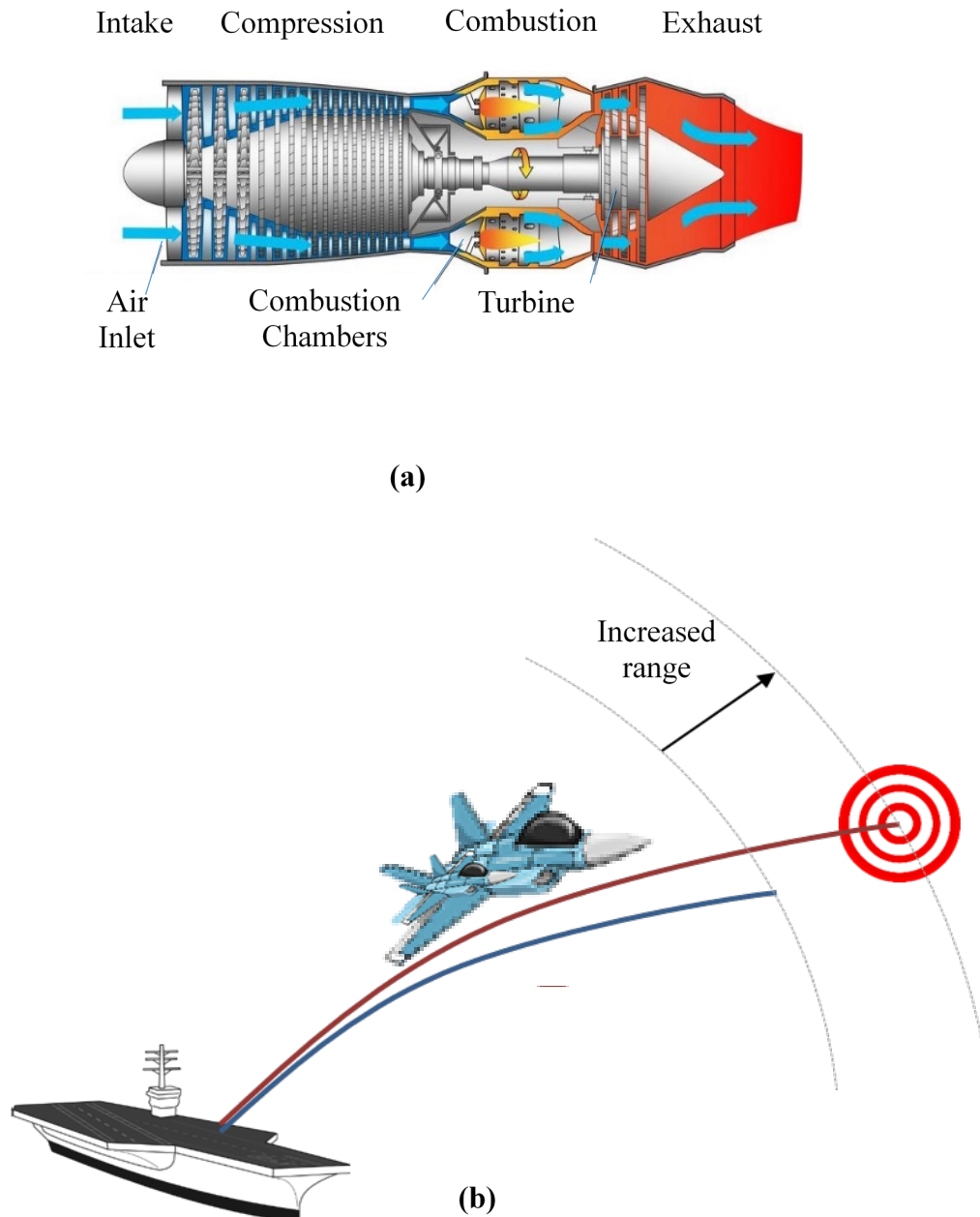


Fig. 6-15 a) Schematic of a turbine system and b) an illustration of the increased range made possible by the more efficient operation of the turbine system (from http://cset.mnsu.edu/engagethermo/components_gasturbine.html)

A piezoelectric element is versatile in that not only can it sense changes in its environment, it can, as a resonator, create sound waves that can be used to interrogate its surroundings. As an example, it can be placed in a nuclear reactor, like the one shown in Fig. 6-16, to monitor the temperature by measuring the speed of sound by detecting the reflected wave from an object a known distance away.

The speed of sound in air increases with the temperature in a precisely documented way, so the changes in the temperature can be accurately measured.

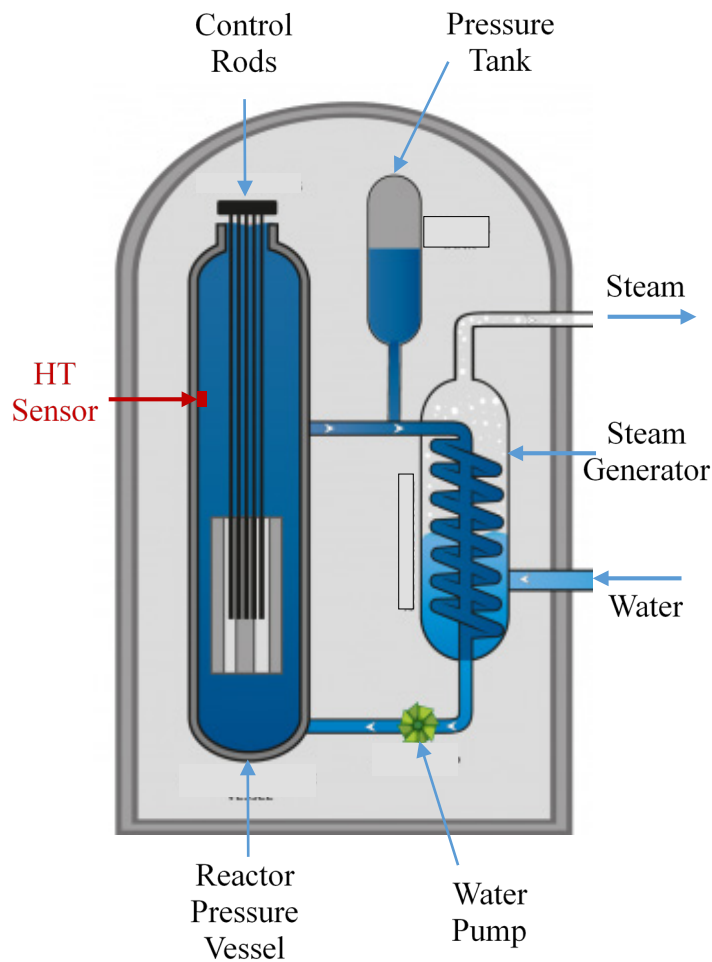


Fig. 6-16 Schematic of a nuclear reactor with a piezoelectric sensor (from <https://www.energy.gov/ne/articles/nuclear-101-how-does-nuclear-reactor-work>)

Nuclear reactors operate at a temperature of only about 300 °C; the corrosive environment created by the nuclear particles is the bigger issue. Current technology uses thermocouples that measure the temperature at a single point. It would be better to be able to survey the temperature of the reactor with a transducer to more quickly detect a hot spot. Early detection improves the chances of avoiding a potentially serious event. It also improves overall performance and can extend the time between routine maintenance.

Ultrasonic transducers can be used to detect physical changes in materials used in infrastructures such as stainless steel piping used in chemical plants that operate at high temperatures (Fig. 6-17). They are able to do this by monitoring changes in the intensity and/or shape of a sound wave that is generated by them. The changes

are caused by defects such as a crack. The interface created by the crack will reflect a portion of the wave, and the reflected wave can be detected. Not only will the monitor be aware that a crack has been formed, but will also be able to locate its position. For many applications, the piping is at a temperature greater than 500 °C, and the chemicals being transported in the piping can create a corrosive environment that attacks the piping. The high temperatures can also locally alter the microstructure of a pipe and weaken it. Early detection of these flaws improves the chances of preventing a serious event.



Fig. 6-17 Hot stainless steel piping at a chemical processing plant

A more complete image of a region, such as of a joint where failure is more likely to occur, can be achieved using an array of individual devices. This array can also be created simultaneously in parallel using techniques similar to those used to create ICs, and devices made in this way are more similar to each other and thus can be packed closer together. Such transducers working in concert with each other to create a single overall image is called a microelectromechanical system (MEMS). At temperatures less than or equal to 500 °C, the electronics used to power these MEMS can be Si ICs, but at higher temperatures, alternatives to the Si ICs have to be developed. Also, replacements for electronic devices that do not function properly at the higher temperatures must be created. One such example would be replacing a transistor acting as a switch with a resonator that can do the same thing. All of this will require piezoelectric materials and their supporting substrates to be developed along with the electrodes used to that stimulate them.

Some individual piezoelectric devices that have been fabricated using AlN films grown on SiC substrates are shown in Fig. 6-18. The first is the piezoelectric micromachined ultrasonic transducer (PMUT). Arrays of AlN PMUTs can be used for short-range and high-resolution ultrasonic imaging. Si wafers can be used for

the low-temperature applications because AlN highly textured films can be grown on them and their processing is compatible with Si CMOS processing.

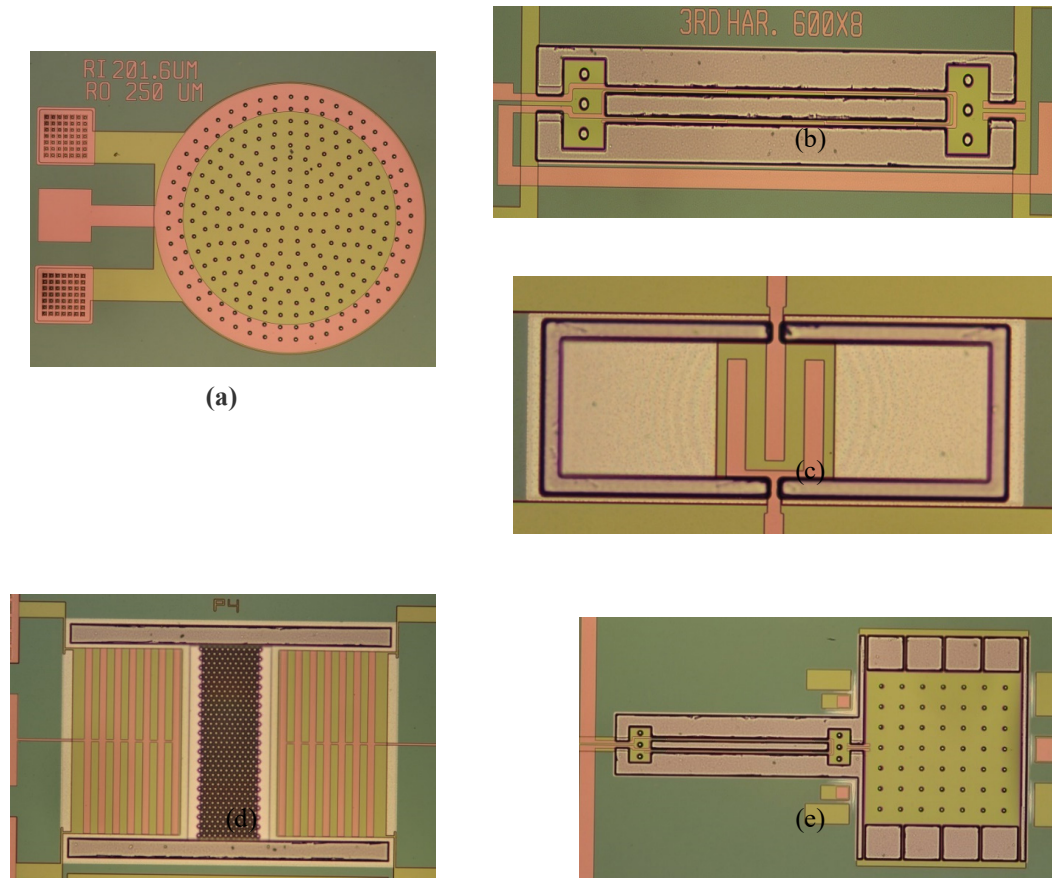


Fig. 6-18 Examples of MEMS devices: a) ultrasonic transducer, b) resonator, c) accelerometer, d) phononic crystal (PnC), and e) double-ended tuning fork (DETF)

The AlN MEMS resonator in Fig. 6-18b has shown great promise toward fully integrated and high-efficiency RF and wireless communication systems owing to its small footprint and low power budget. The need for ultra-low-power communications and sensor systems is growing, and recently MEMS resonator technologies have been demonstrated as fundamental building blocks in near-zero power sensors for various application areas.

There are electrostatic, piezoresistive, pyroelectric, and piezoelectric MEMS accelerometers like the one shown in Fig. 6-18c. The piezoelectric type has a higher energy transfer efficiency and a simpler structure. MEMS accelerometers and gyroscopes are widely used in inertial navigation systems where information provided by them assist in providing the position and orientation of an object relative to a predetermined origin point, orientation, and speed. MEMS accelerometers have enabled the manufacture extremely small and light inertial navigation systems. These systems broadened the range of potential applications to

areas like video motion capture. A typical MEMS resonant accelerometer contains resonant elements and proof masses. When an in-plane inertial force is applied on the MEMS structure, the proof mass will tense or compress the resonant elements leading to a change of the stiffness. Therefore, the resonance frequency shifts with the increase of the in-plane inertial acceleration. Because of its piezoelectric properties, AlN MEMS accelerometers have the ability to eliminate this problem by being able to measure acceleration out-of-plane while resonating in-plane.

The PnC displayed in Fig. 6-18d is a periodic structure imbedded uniformly in another medium such as a periodic array of AlN rods imbedded in air. When the periodic distance between the rods creating the structure is of the order of the wavelength of the sound being transmitted through it, they can have a profound effect on it—they can disallow any waves over a given frequency range to pass through it. As is the case in semiconductors where there is an energy gap for electrons, there is an energy gap for sound waves in PnCs. This characteristic can be exploited to confine, wave guide, and focus mechanical energy with little loss while doing so. The ability to do this is utilized in wireless communications, optomechanical coupling devices, modulators, and related areas.

Applications of PnCs combined with MEMS interdigitated transducers (IDTs) and micro-resonators to engineer different types of filters or acoustic sensors have attracted much interest recently. High-quality-factor acoustic cavities or waveguides can be fabricated with a very small volume using PnCs. This has enabled AlN transducers to operate at frequencies close to 1 GHz.

DETFs, like that seen in Fig. 6-18e, are one of the most sensitive elements in MEMS resonator sensors such as resonant accelerometers, resonant gyroscopes, and some resonant biosensors. Such sensors mainly comprise comb actuators, a proof mass, two symmetrically distributed amplifying leverage mechanisms, and DETFs. They measure the applied signals by detecting the resonant frequency shift of the sensitive element. The DETF mainly consists of two beams, which can be considered as double-clamped beams. In the constant state, the two beams work in a resonant state and have a 180° phase difference to minimize the energy losses. The resonant frequency of every beam can be acquired by the self-designed closed-loop circuit of excitation and detection or auxiliary test equipment such as a laser vibrometer. With the attractive advantages of high sensitivity and frequency output and a wide dynamic range, they are used in many different areas such as aeronautics, astronautics, vehicle automation, and mobile image stabilization.

Devices based on Si have been shown to be highly sensitive strain sensors that can be used to measure localized strain fields because of their small size. These Si-based sensors rely on electrostatic actuation and capacitive readout, and require

large actuation and bias voltages. They also require special circuitry, such as square wave oscillators, in order to be capable of operating in air due to the large damping of their comb fingers. In contrast, AlN-based piezoelectric DETF devices can be operated with standard resonator circuits in air using very small actuation voltages. When used as strain sensors, they require very small chip area because they are not required to have comb fingers. Therefore, measurements of strain gradients over a very small area using an array of such devices are conceivable. Besides the reduced form factor and enhanced operation at atmospheric pressure, harsh environment survivability is another major advantage of the AlN DETF. In combination with high-temperature circuitry, such sensors could operate inside of combustion engines, turbines, or geothermal wells.

6.3.2 Individual Devices

6.3.2.1 Monitoring Pressure Changes in High-Temperature Compartments^{1, 2}

The change in the pressure of the turbine compartment is measured by the change in the charge on the face of a piezoelectric crystal, as shown in Fig. 6-19b. The rate of change of charge is a current that is the quantity that is measured. It is necessary for the element to be quite sensitive; it should be able to pick up useful output signals from strains as small as 0.1%. The signals produced by most piezoelectric elements are quite uniform over a large pressure range; the output signal can be linear over a wide range, typically 0.7 KPa to 70 MPa (0.1 to 10⁴ psi) with an accuracy of about 1%. Ceramic sensors, such as those made from LGS, are subject to a loss of sensitivity of approximately 1% per year. AlN elements have not been studied in sufficient number to quantify their sensitivity, but considering their potentially more defect-free structure, it is likely they could do better.

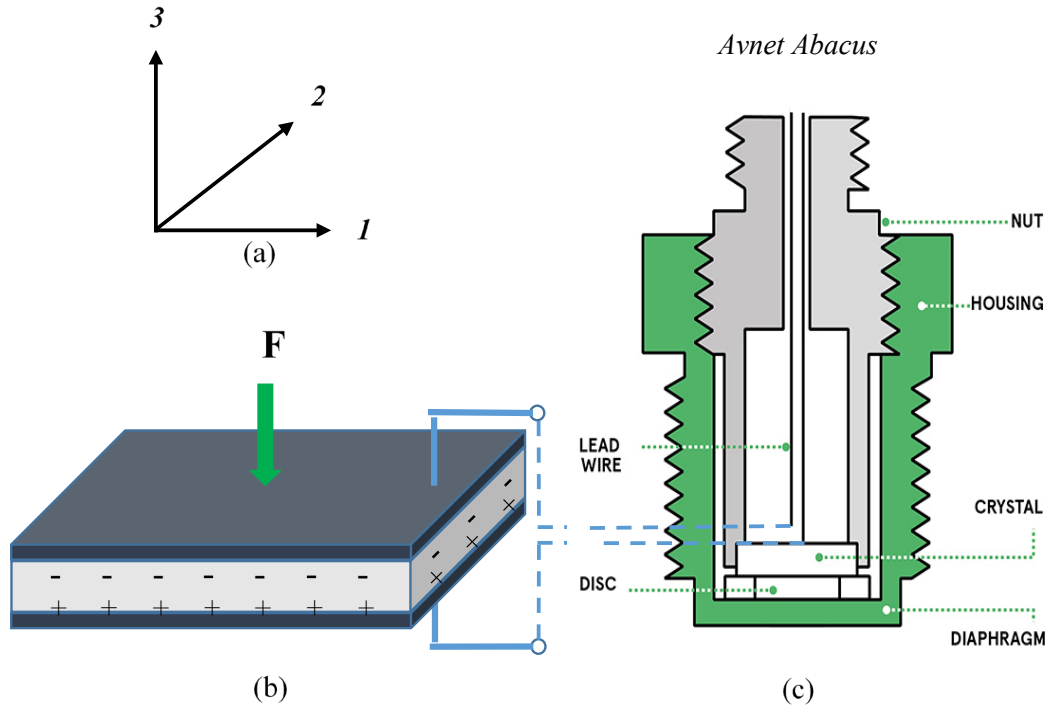


Fig. 6-19 a) Reference Cartesian coordinate system for the piezoelectric crystals, b) piezoelectric crystal with electrodes, and c) the casing used when acting as a pressure sensor

The signal is small, so every effort must be made to minimize stray signals. Typical values for the piezoelectric coefficient are in the tens or hundreds of picocoulombs per meters squared per newton per meters squared. One newton is a significant amount of force, whereas 100 pC is a miniscule amount of charge. In many cases, it is useful to use an amplifier that can convert the sensor's charge into a usable signal, so charge amplifiers for piezoelectric sensors are frequently used; a charge amplifier is an integrator with very high input impedance and the integration functionality converts charge into voltage. The high input impedance ensures that the small amount of charge generated by the piezoelectric transducer is not lost through leakage.

6.3.2.2 Monitoring the Temperature in a High-Temperature Corrosive Environment

Piezoelectric sensors are also used to measure changes in the temperature in a nuclear reactor to improve its performance and safety. An example is the nuclear reactor shown in Fig. 6-16, which operates at about 300 °C; the corrosive environment created by the nuclear particles is a bigger issue. The temperature change is measured by the change of the speed of sound in the air inside of the reactor with the sound wave being created by a resonance process different than that used to create small displacements in the element. Instead, the entire element

is made to vibrate by setting up a sound wave within the crystal that is cut to a thickness of one half the wavelength of the sound wave in the material. AlN has a relatively large longitudinal velocity parallel to the *c*-axis—10,750 M/s—so its wafer can be thicker for a given desired frequency compared to many other piezoelectric materials.

The speed of sound in air is equal to $20.05\sqrt{T}$, where *T* is the absolute temperature. The dependence on pressure and humidity is much less, but if necessary can be accounted for by a simple program in the receiver electronics. The speed of sound in the reactor is determined using the pulse echo technique with a sound wave created by a piezoelectric resonator operating at its resonance frequency to maximize the amplitude of the wave. Given that the largest longitudinal piezoelectric constant is often parallel to the piezoelectric axis, it is likely that the element is a wafer with its surface normal to the 3-axis. It is important for the front and back faces to be as parallel as possible. For a fundamental resonant frequency to be 20 MHz, the thickness of the element will be approximately 100 μm . The ultrasound transducer and fixture assembly is similar to that used for measuring pressure changes shown in Fig. 6-16c. The primary difference is there are two piezoelectric transducers—one to generate the sound wave and another identical transducer used to detect the echo.

Theoretically, radiation can damage material by colliding with atoms in the lattice and creating point defects such as vacancies and interstitials. This can profoundly affect the electrical and optical properties of semiconductors, but it seems to have much less of an effect on their piezoelectric properties. That crystalline defects do not have such profound effects on the piezoelectric properties as evidenced by the frequent use of polycrystalline material for the active element. However, piezoelectric elements do have a limit in that when bombarded with high-energy nuclear particles for a sufficient amount of time, they will become amorphized and lose or have greatly diminished piezoelectric properties. The questions then are, what materials are the most radiation tolerant and what is the radiation tolerance for each of these piezoelectric materials? A theoretical study suggests that AlN is one of the most radiation tolerant of the high-temperature piezoelectric materials because it has a relatively simple structure and its bonds have a relatively high degree of ionicity.³

Experimental degradation studies have been done with AlN, zinc oxide (ZnO), and/or bismuth titanate ($\text{Bi}_4\text{Ti}_3\text{O}_{12}$) transducers by testing them before and after they were exposed to fast neutrons and gamma rays.^{4,5} Tests of bulk single-crystal AlN were done in a TRIGA nuclear reactor core that showed this material to be completely unaffected by a fast and thermal neutron fluence of 1.85×10^{18} and 5.8×10^{18} n/cm², respectively, and a gamma dose of 26.8 MGy.⁴ Using in-situ

instrumentation with wireless transmission capabilities to provide real-time data on fuel performance phenomena, researchers⁵ found that a $\text{Bi}_4\text{Ti}_3\text{O}_{12}$ sensor was capable of transduction up to $5 \times 10^{20} \text{ nf/cm}^2$, a ZnO sensor up to $6.27 \times 10^{20} \text{ nf/cm}^2$, and the AlN sensor up to at least $8.65 \times 10^{20} \text{ nf/cm}^2$. The words, “at least” were used because the AlN sensor maintained its initial transduction efficiency to the end of the experiment. In a related experiment, quartz was shown to degrade at fluences of about $9 \times 10^{19} \text{ n/cm}^2$ due to amorphization of domains, as measured by X-ray spectroscopy.⁶

6.3.2.3 Flaw Detection in Structures Operating at High Temperatures

Sound waves are used to detect flaws in solids by measuring the time between when a wave is created and when its reflected wave is detected by an ultrasonic transducer, as well as by analyzing the intensity and the shape of the detected wave. As was the case in monitoring the pressure in the combustion chamber of a jet engine, there is a similar need to be able to monitor physical structures by probing them with sound waves. Processing industries, where hot metal pipes or tanks must be tested without shutting them down for cooling, utilize these measurements, as do manufacturing processes that involve hot materials before they have fully cooled.

The sound wave that is created can be a bulk wave generated by an ultrasonic transducer. As illustrated in Fig. 6-20, the wave can be normal to the surface and the detected wave is the wave reflected from the backside of the work piece. One frequent use is to determine the thickness of the work piece when the speed of sound in it is known and the time for the wave to be transmitted to and reflected back from the other side is measured. This information can be used to determine to what extent the inside of the pipe has been corroded. The accuracy of this measurement is determined by how accurately the speed of sound in the material is known.

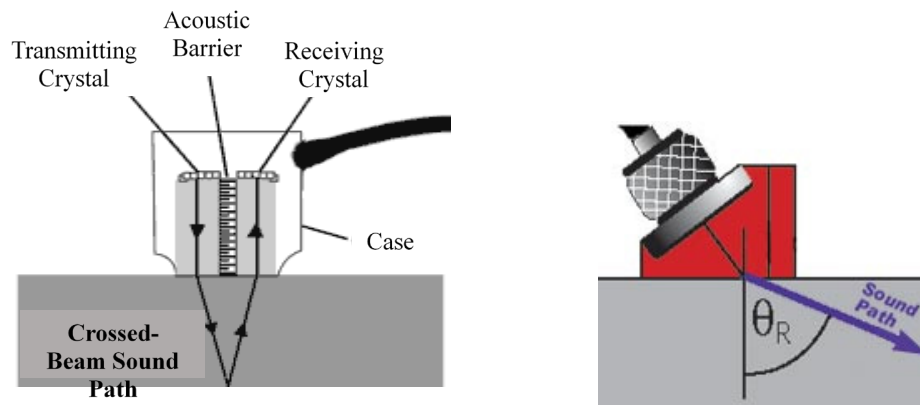


Fig. 6-20 Schematics of a) a normal contact transducer and b) an angle beam contact transducer

The advantages of using this method to determine the thickness of plates are that the method is nondestructive; it does not require access to both sides of the sample; it can be engineered to cope with coatings, linings, and so on; good accuracy (0.1 mm and less) can be achieved using standard timing techniques; it can be easily deployed; it does not require laboratory conditions; the equipment is relatively cheap; and there is no need to remove the metal coating. The disadvantages are that it usually requires calibration for each material, good contact with the material, and coupling material between the measured surface and the probe, and cannot take measurements over rust.

Bulk waves can also be inserted into the test piece at an angle, as illustrated in Fig. 6-20b. They are somewhat harder to track because wave propagation is strongly influenced by Snell's laws of transmission and reflection, but this enables them to be used to monitor the propagation of cracks. Although the intensity of the reflected beam from the crack will be much less than the one from the backside due to the difference in the impedance of the cracked region and that of the surrounding medium is much smaller than it is between the surrounding medium and the backside surface, the beam can be detected. One can determine how much the crack grows by monitoring it over time. There is also a need to continuously monitor the local microstructures of the pipes, as they can be altered at high temperatures by the annealing process. These changes can weaken and/or embrittle the metal. They too can be monitored because a change in the microstructure can sufficiently alter the material's impedance, which can be detected.

The generic ultrasonic transducer used primarily for making thickness measurements on flat sheets comprises an active element, backing, and a wear plate inside a metal casing with the necessary contact wires. The requirements for the active element is that it has a reasonably large piezoelectric constant for generating the type of wave that will be used at the temperature the device will be operated. The common modes used in ultrasonic flaw detection are shear and longitudinal waves propagating perpendicular to the plane. The element is also $\frac{1}{2}\lambda$ thick so that the waves reflected inside of it will be in phase with those being created.

The basic purpose of the wear/matching plate for a flat plate contact transducer is to protect the element from the testing environment. It must be a durable and corrosion-resistant material to withstand the wear caused by the materials such as steel being examined. It should also be smooth to optimize the power inserted into the steel plate. Al_2O_3 is often the material that is used, and these plates are often replaceable. A liquid coating couplant is often used to increase the energy of the wave injected into the test piece by reducing the scatter from its not-so-smooth surface.

Angle beam transducers are transducers mounted on a wedge that makes an angle other than 90° with the surface of the test piece (Fig. 6-20b.) They are typically used to introduce a shear wave into the test material at an angle not equal to 90° because they are not as refracted. They can have a fixed angle or the angle can be adjustable, determined by the user after deciding what the angles of incidence and refraction should be. The angles are usually chosen so that the reflection coefficient for the metal/air boundaries are 100%. Angle beam transducers are also used to generate surface waves for use in detecting defects on the surface of the test piece.

Conventional ultrasonic transducers will tolerate temperatures up to approximately 50°C (125°F). Above these temperatures, differences in their thermal coefficients of expansion (TCEs) will likely break some of their bonds, so making transducers that will work up to 500°C is challenging and making ones that will work between 500 – 1000°C is even more challenging.

In addition to finding materials that can survive and remain piezoelectric at these higher temperatures, one has to deal the fact that the attenuation of the sound in all materials increases with temperature. The effect is much more pronounced in plastics than in metals or ceramics. In a typical fine-grain carbon steel alloy, the attenuation at 5 MHz at room temperature is approximately 2 dB per a 100-mm one-way sound path; at 500°C , the attenuation increases to approximately 15 dB per 100 mm of the sound path.

Contact transducers have the advantage of being able to make measurements at any point of the test piece, but this is also a disadvantage because one has to continuously make a new contact. The operator will also have to deal with handling an extremely hot element, but this can be mitigated by using a delay line. Delay lines up to 1 m long have been developed. In an effort to keep the instrument as cool as possible, the standard high-temperature transducers operate with a duty cycle. The recommended duty cycle for surface temperatures between 90 and 425°C is no more than 10 s of contact with the hot surface followed by a minimum of 1 min of air cooling. Also, some users employ water cooling.

One of the most difficult challenges is finding a couplant that works at elevated temperatures. Inspections made at room temperature almost always use a fluid couplant layer to produce a good acoustical contact. The procedure can be done at any point on the test piece and the test piece does not have to be modified. But attempts to adopt a similar approach to high-temperature applications presents special difficulties. Most common ultrasonic couplants such as propylene glycol, glycerin, and ultrasonic gels will quickly vaporize if used on surfaces hotter than 100°C . Proprietary high-temperature coupling pastes and fluids are available, but they tend to evaporate or dry out rapidly above 300°C and thus are suitable only

for instantaneous point measurements. An alternative is to use low-melting-point solder glass, which, although more stable, still introduces the problem that it can corrode the test component and/or cool the test component.

Some of these problems can be mitigated by using a brazed transducer.⁷ One advantage is that it does not need a couplant because it is bonded in place using a special type of bond. It has the obvious disadvantage in that it cannot be moved around, but if there is a region that has to be focused on, such as a welded joint, the fact it cannot be moved around is a moot disadvantage.

However, this fixed contact will have to be able to withstand the stresses at the interfaces created on cool down to room temperature due to the materials' different TCEs. The acoustic properties of the braze are usually not particularly important because the wavelength of the sound created is typically greater than 10 times longer than the brazing layer is thick.

Reliable wide-bandwidth and low-noise ultrasound transmission has been achieved up to temperatures as high as 800 °C. For the particular setup used in the experiment discussed⁸ here, only the fundamental modes were able to propagate, and they were able to travel several meters in the stainless steel plate. The detector was an AlN *c*-oriented single crystal wafer operating in the thickness extension mode that detects the changes in the electric field of the wave normal to the stainless steel surface and the direction of propagation of the wave. Being AlN, the element has a relatively large d_{33} made even a little bit larger by the fact it was a single crystal and not the usual highly *c*-axis oriented polycrystalline film. Both the element and electrodes appeared to be stable to temperatures up to 1000 °C. The large difference in the CTE of the AlN and stainless steel along with the decaying of the electrodes limited the upper operating temperature to approximately 800 °C.

While a straight-line crack requires only one measurement by one transducer to measure changes in its length, it takes measurements made by the same transducer at numerous positions to keep track of a crack with a more complex flaw. There could also be a number of cracks one would like to track at the same time. One way to solve this problem is to have an array of transducers at a single position. This can be achieved using only one acoustic bond between a piezoelectric plate and the test piece.⁹ As noted earlier, this could also be done by a MEMS imager.

6.3.3 High-Temperature Integrated MEMS

6.3.3.1 Devices

Recently, the size of piezoelectric devices has become an important factor for integrated systems, as smaller devices have advantages of higher sensitivity,

reduced noise levels, low power consumption, multi-functionality, and batch production. The small size of the individual elements provides the ability to form compact multi-sensor arrays that can be used to create sensors and actuators possessing bandwidth and spatial resolution that are often not possible with mainstream mechanical fabrication techniques. These features are key reasons as to why the device industry adopted MEMS technology for advanced sensors and actuators.

The pixels of the array could be individual devices with their own active piezoelectric element that are as close as possible identical to each other. They can also be created using a thin-film device structure grown on a substrate wafer that is processed much like an IC is. Making use of the highly developed technology created by the IC industry, they can be made more cheaply and also have better uniformity. They also can be fabricated directly onto an IC that can provide the electrical intelligence to run them. When the MEMS are made a part of the IC, they are often referred to as a system on a chip.

Because they can be made so small, MEMS can have device properties that are superior to those of an array of individually made devices. The main performance parameters of a transducer include the operating frequency, bandwidth, acoustic impedance, and effective coupling coefficient. The thickness of the element does not dictate the operating frequency; the membrane resonance frequency does. Thus, the frequency is governed by the dimensions and the layering materials of the membrane, and can therefore be controlled independently of the element layer thickness offering more design flexibility and control over the frequency. The overall thickness of the membrane does to a great extent determine the maximum frequency for which the device can be built, and the layers in the PMUTs can be made very thin to achieve higher frequencies. The element thickness for an array made up of individual transducers cannot be made reproducibly thin enough to reach the high frequencies desired for a number of applications.

The bandwidth, the width of the frequency range over which the transducer exhibits a significant response, is a basic FOM, as it implies a shorter impulse response time and therefore a better system resolution. The bandwidths of PMUTs are up to 100% larger than similar systems comprising arrays of individual elements, which enables considerable design flexibility and allows their operation frequency and acoustic impedance to be tailored for many applications. Being able to adjust the acoustic impedance to closely match the acoustic impedance of the load medium enables the device to transfer the maximum amount of energy.

A resonator, as well as a PMUT,¹⁰ has been fabricated using the xMEMS process, which utilizes AlN films grown on SiC substrates.¹¹ As noted earlier, a resonator is

a piezoelectric crystal oscillating at a resonant frequency, where it can be used for such functions as a filter or timing piece. In this case, it is an AlN free-standing resonating plate vibrating longitudinally in the plane of the plate when an electric field is applied normal to it. It utilizes the piezoelectric effect associated with d_{31} . This resonator favors the length-extensional mode shape due to the anchors along the center axis of the plate parallel to the 2-direction, as shown in Fig. 6-21a. This type of resonator is called a contour-mode resonator (CMR).¹² The CMR operates in the transverse direction, of which the frequency is defined by in-plane dimensions and independent of the piezoelectric layer thickness, so devices of different frequencies can be manufactured and integrated on a single chip. From this perspective, it is beneficial to realize multi-frequency integration. AlN has a high acoustic velocity, low intrinsic material loss, low frequency temperature coefficient, and good thermal conductivity, which makes it more suitable for fabricating high frequency and Q value devices; they routinely have Q values of 1000–4000.

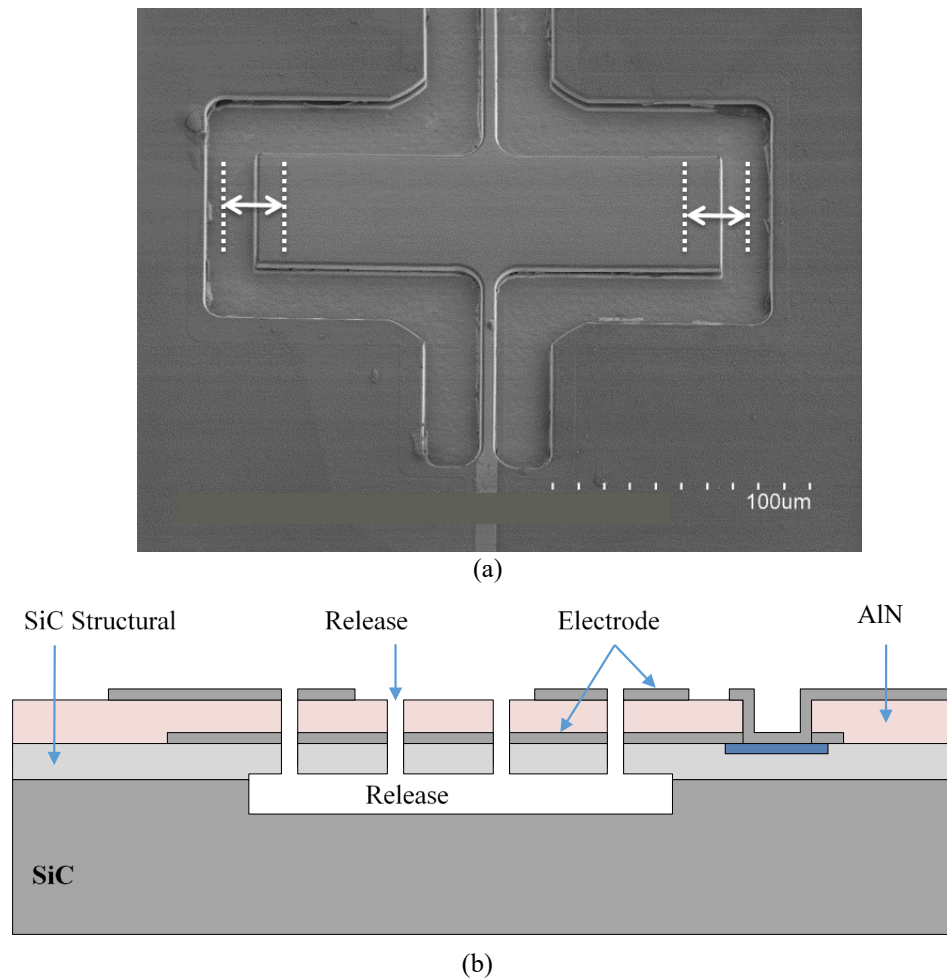


Fig. 6-21 a) Micrograph of the contour resonator and b) schematic of its construction

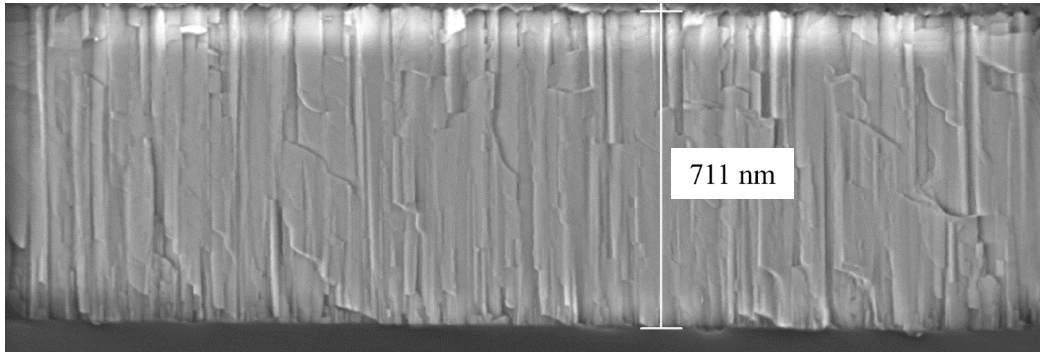
The device structures for many of the different devices are quite similar; the devices are differentiated by the way the structures are processed. The SiC cavity substrate can be created by growing a SiC film on a Si wafer.¹³ They are grown to a thickness of approximately 1 μm by the LPCVD (250 mTorr) technique at 950 °C on the (100)-oriented Si wafer using a gaseous mixture of dichlorosilane (SiH_2Cl_2 , DCS) and dichloroethylene ($\text{C}_2\text{H}_2\text{Cl}_2$, DCE). The film has a 6H structure (also called α -SiC) with a (0001) texture. The DCE/DCS flow ratio controls the residual film stress. The cavity substrate can also be a high-quality, single-crystal SiC wafer, as shown in Fig. 6-21b.

The mask used to fabricate the cavity is a hard dielectric mask created by a thin, low-stress silicon nitride film deposited on the substrate surface followed by the deposition of a thicker SiO_2 layer. The SiO_2 is patterned and etched exposing the SiC substrate that is selectively deep reactive-ion etched to a depth of 4 μm , and then the SiO_2 is selectively etched off leaving the silicon nitride layer intact so it can later be used as an etch stop. A polycrystalline (poly) Si film is deposited over the entire surface of the substrate filling the cavities in the process. The poly-Si is patterned to protect the poly-Si covering the cavities, while the rest of it is etched off to increase the speed and uniformity of planarizing the wafer that is done using a chemical mechanical polish (CMP) to planarize the wafer down to the silicon nitride etch stop. Then the silicon nitride is selectively removed with a wet etch.

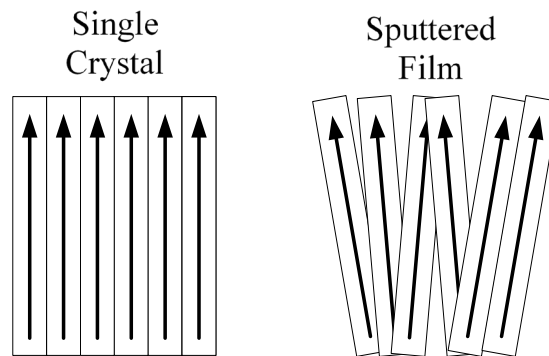
A 2- μm α -SiC handle substrate, also called a structural film, is deposited over the entire wafer, and a CMP is performed on the film to reduce the SiC roughness to the nanometer level, and in so doing, reduce the thickness of the SiC to approximately 1 μm . The poly-SiC is patterned and a shallow cavity is etched where a tungsten (W) plug for the bottom electrode contact will be created. A W film is deposited, patterned to protect the W in the etched plug cavities, and is then etched.

To fabricate the lower electrode the first step is to deposit a 50-nm tetraethylorthosilicate (PETEOS) layer by plasma enhanced sputtering. It is used to give the 20 nm Ti adhesion layer and 200-nm titanium nitride (TiN) contact layer, a preferential orientation that will encourage the preferential *c*-axis orientation of the AlN layer grown on it, which will maximize the piezoelectric constants.

The piezoelectric element is a highly (0002) textured, 710-nm AlN film that is sputter deposited, and a cross section of it is displayed in the SEM micrograph shown in Fig. 6-22a. It was deposited by pulsed DC reactive sputtering of Al in a N_2 and argon (Ar) environment at 350 °C. The sputter deposition conditions and substrate material and surface roughness were varied to achieve the highly *c*-axis texture. The full width at half maximum (FWHM) of the (0002) X-ray rocking curve is often used to characterize the crystallographic texture of the AlN film.



(a)



(b)

Fig. 6-22 a) Micrograph of the highly textured AlN film sputtered onto the textured TiN bottom electrode illustrating its *c*-oriented columnar grains. Schematic of b) perfectly aligned columnar grains and the slight disorientation of them that accounts for the slight broadening of the (0002) rocking curve.

A more important consideration than obtaining the maximum value for d_{33} is to make certain that its value for a given temperature does not change over time. This could happen, for example, if the structure changed over time when operating at a high temperature. The columnar grains could become more aligned through a process of recrystallization where one grain could grow at the expense of another with the driving force being lowering the free energy by making a more perfect crystal. This does occur for these films, as indicated by the fact that the FWHM decreases from 1.8° to 1.7° when the film is annealed for 3 h at 950°C , but this small change does not have a noticeable permanent effect on the piezoelectric constants.¹⁰ Another concern is that too many repetitive changes in the temperature and the stresses created by the materials' CTEs could cause the devices to deteriorate.¹⁴

As illustrated in Fig. 6-22b, a via is etched through the AlN to the bottom Ti/TiN electrode in the region just above the W plug. This is followed by depositing the

top electrode, which is a 200-nm TiN film. It is deposited and patterned to form the top electrode as well as a contact to the bottom electrode.

Finally, the devices must be released from the substrate so they can freely operate. As illustrated in Fig. 6-22b, release holes are etched through the film stack to the poly-Si occupying the cavity. It is selectively etched away using a xenon difluoride etch.

Knowing that the length of the resonator in Fig. 6-21a is 180 μm and weighting the elastic modulus and the density by the fraction of the thickness of the plate, the electrodes, piezoelectric element, and the structural bar they make up, one can calculate the speed of sound and the resonant frequency. Doing this yields $v_s = 10.26 \text{ km/s}$ and the resonant frequency, $f_e = 28.53 \text{ MHz}$. This is surprisingly close to the measured value of 28.52 MHz. The S12-parameter response was measured as a function of the frequency to determine the series resonant frequency, f_s , and parallel resonant frequency, f_p , which can be used to calculate the effective electromechanical coupling coefficient, k_{eff}^2 ; it was found to be 0.31%. f_s and f_p were obtained from the maximum and minimum of the S12 response. The quality factor, Q , being the ratio of f_s and the peak width at 3 dB can also be found from the S12 response; it was 1300. The calculated k_{eff}^2 is low compared to microresonators fabricated using handle substrates other than SiC because they are less stiff;¹⁵ their Young's moduli are smaller.

The resistance due to the electrical leads was larger after the resonator was heated. To combat this, future devices could use platinum (Pt) on the electrical lines to minimize the lead loss. The importance of having electrodes that do not deteriorate at the higher operating temperatures is discussed in the next section.

The resonators were tested in situ at elevated temperatures to see if there was any hysteresis in some of its properties indicating that they had been altered by changes in the structural properties of the piezoelectric element. The resonator was heated to 935 °C for 5 min in Ar with a pressure less than 1 Torr, cooled down to room temperature, and then it was heated in air with the temperature increased in 50 °C increments up to 500 °C, then decreased in 50 °C increments down to room temperature. Both the resonant frequency and k_{eff}^2 were measured, and, as seen in Fig 6-23, neither property exhibited any hysteresis, suggesting the resonator was stable in air up to 500 °C. The resonant frequency decreases as the temperature increases, not because there is any deterioration, but because Young's modulus, and therefore v_s decreases.

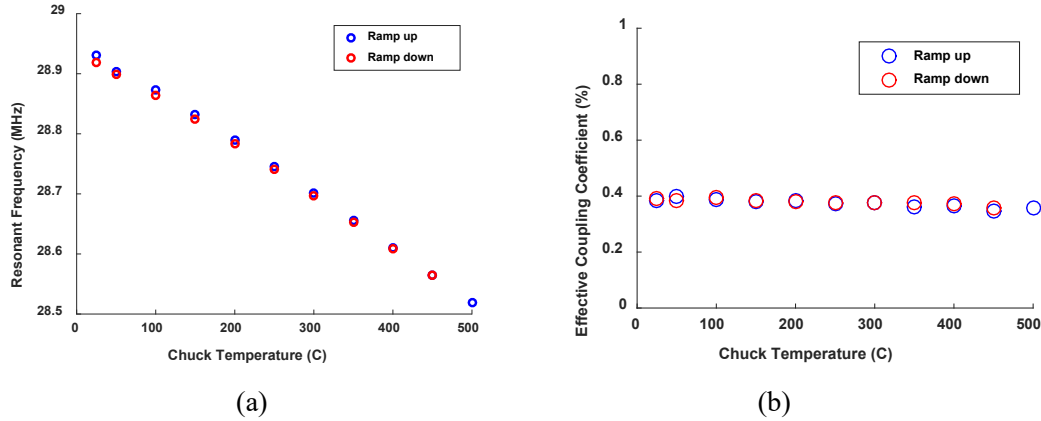


Fig. 6-23 The a) resonant frequency and b) effective electromechanical coupling coefficient of a resonator plotted as a function of temperature with measurements made both during the heat up and cool down cycles

6.3.3.2 High-Temperature Electrodes

Pt is the premier metal contact because of its high melting point (1773 °C), nearly constant bulk resistance temperature coefficient, resistance to oxidation, and ease of deposition such as by sputtering.¹² Although a very thin (~1 nm) surface oxide exists at room temperature, it disappears at temperatures above 400 °C,¹⁶ and no other oxide is observed up to 1000 °C. It also has been determined that volatile oxides do not form, because no weight change is detected when it is heated in air up to 1000 °C.¹⁷ The primary way the Pt film deteriorates is physically through agglomeration or delamination. A Pt electrode with the desired 100-nm thickness degrades at temperatures, $T > 700$ °C; the T is higher for thicker films.¹⁸ While the stability of metal electrodes on bulk-acoustic-wave resonators can be ensured by deposition of thick Pt films (e.g., 3 μm), the electrodes on surface-acoustic-wave (SAW) resonators should not exceed a thickness of 100 nm due to the influence of the electrode mass on the acoustic waves they help to create.¹⁹ This agglomeration process is driven by the surface tension of the film and high surface-to-volume ratio of these thin-film electrodes. Surface diffusivity acts to reduce the surface area through a nucleation and growth process.¹⁸ The grains grow larger and thicker, and in so doing, separate into metal islands that do not necessarily touch each other, and that greatly increases the resistance of the electrode. The stresses created by the differences in the TCEs can accelerate the process. When they are large enough, they can cause delamination.²⁰

Sealing the device with a thin ceramic coating can diminish this problem. Tests with alumina-coated samples increased the lifetime of the metallizations possibly because it slowed the in-diffusion of O.²¹ After annealing the capped structure at a temperatures of 800 °C, no significant change was visible. A degradation of the

layer was visible only at temperatures of 900 °C and above.¹⁹ By creating a Pt10%rhodium (Rh) alloy and sealing the electrode with a 25-nm N-rich SiAlON ceramic cap, the electrode is stable at 1000 °C.^{19,22,23}

Electrode materials often require an adhesion layer as the unreactive noble metals do not form strong bonds with the substrates either. An intermediate layer of a less noble metal has to be inserted between the electrode and the substrate to improve the adhesion of the electrode to it, and Ti has been found to work best for Pt on most substrates and piezoelectric elements.

The transition metal compound TiN²⁴ can act as high T electrodes, because it has a high melting temperature (2950 °C) and the *d*-electrons in the unfilled *d*-shell are available for conduction. The bulk resistivity can be as low as 13 μΩ·cm, but thin-film electrodes often have a larger resistivity, because it is highly dependent on the grain size²⁵ and the grains in the deposited electrodes are usually too small. They are more likely to have a resistivity of approximately 100 μΩ·cm. The grain size is important because the mean free path of electrons is limited by scattering at the grain boundaries²⁶. TiN films that were annealed in the air at 500 °C for 2 h had only an atomic layer of TiO₂ on their surface, but XRD spectra showed that rutile, TiO₂, appeared above 600 °C.²⁷ It is possible this T could be raised by protecting the TiN with a thin ceramic coating.

The solid oxide lanthanum strontium magnetite (La_{0.65}Sr_{0.35}MnO₃, LSM), is quite conductive, because it also has an unfilled *d*-shell. However, its resistivity of 4.3×10^3 μΩ·cm at 900 °C²⁸ is more than 100 times larger than that of Pt, and at lower temperatures, it is much greater than that. Heavily *n*-doped SiC has also been considered as an electrode, because it would be stable to at least 1500 °C if it could be protected from being oxidized, but its relatively large resistivity of 10³ μΩ·cm is off putting.

6.3.3.3 High-Temperature Piezoelectric Materials

Of the popular piezoelectric materials AlN, ZnO, SiO₂ (α-quartz), gallium orthophosphate (GaPO₄), and LGS and the ferroelectrics lithium niobate (LiNbO₃) and lead zirconium titanate (Pb_xZr_{1-x}TiO₃, also called PZT), only AlN and LGS are both piezoelectric and chemically stable at the higher temperatures, 800–1200 °C. AlN does begin to oxidize at 800 °C, but the thin oxide created on it protects it until the temperature, T, reaches 1370 °C. Some believe that a surface oxide layer 5–10 nm thick is formed that can protect the AlN from further oxidation up to 1370 °C.^{29,30} LGS becomes ionically conductive and also quite lossy when T > 1000 °C. PZT ceases to be ferroelectric before T reaches 400 °C, and α-quartz transforms to β-quartz at 573 °C and GaPO₄ transforms to another phase at 970 °C,

and neither of the high-temperature phases are piezoelectric. Also, the piezoelectric phase becomes quite lossy 200 °C below their transition temperature. ZnO and LiNbO₃ preferentially lose O and become lossy at $T < 500$ °C.

AlN has three independent piezoelectric constants—two associated with longitudinal stresses, d_{33} and d_{31} , and one associated with shear stresses, d_{15} . When compared with other semiconductors, it has some of the largest values. This is due to the facts that AlN has the hexagonal wurtzite structure, and the bonds are more ionic. d_{33} , with the 3-axis being parallel to the c -axis is often associated with sensors such as the pressure and temperature sensors discussed in earlier sections. It is also the piezoelectric constant usually used to define k_{eff} , the effective electromechanical coupling coefficient; d_{31} is often the piezoelectric coefficient associated with resonators such as the one discussed earlier.

The variation of its piezoelectric properties with temperature is small. This is advantageous because piezoelectric devices focus on measuring changes in properties created by outside stimuli, as opposed to measuring their absolute values, so there is a desire that the magnitude of the element's piezoelectric properties remain as constant as possible. Measurements show that d_{33} remains relatively constant between room temperature and 300 °C.³¹ The small thermal coefficients of expansion of AlN enable it to have small thermal drifts.

The loss in the AlN films, as represented by $\tan\delta$, is small. Conduction losses are small because AlN is a UWBG semiconductor with an energy gap of 6.2 eV and few electrically active point defects so it can be quite easily be prepared with a resistivity greater than $10^{13} \Omega\cdot\text{cm}$.³ There is no ionic conduction because the atoms are held tightly in place by their covalent bonds. Breaking, then remaking the bond after movement, would have to overcome a large activation energy. Internal mechanical, sometimes called frictional, losses can be caused by movement of point, line, and/or internal surfaces such as grain boundaries and ferroelectric domains. Most AlN piezoelectric elements are thin, highly oriented polycrystalline thin films. The grains are parallel to the c -axis, and their small angle grain boundaries can be described by slight rotations about it relative to each other. There is evidence that piezoelectric induced slippage of the grains relative to each other occurs, but the effect is very small.

Very few bulk AlN crystals are grown and cut into wafers to be fabricated into individual devices; they are too difficult and expensive to grow, and other materials have better properties for these types of applications—especially those done at room temperature where ferroelectric materials and quartz are particularly effective. The vast majority of AlN piezoelectric devices are fabricated from AlN

films because good-quality films can be easily deposited at low cost, and they can be readily processed into many devices much like what is done for making ICs.

The primary growth method for the growth of the AlN films is sputtering because the deposition process should be CMOS compatible for low-T applications, and they are often deposited on what becomes the lower electrode, which often is a metal. A low growth temperature of less than or equal to 500 °C is required to be CMOS compatible, and also to prevent the metal from oxidizing. However, the temperature has to be high enough so that the crystallites are aligned parallel to the c -axis. The method of choice is magnetron reactive ion sputtering using an Al target and N₂ and Ar gas.³² The substrate surface for CMOS applications is the amorphous SiO₂ surface. AlN films have been demonstrated in a monolithically integrated post-CMOS process.³³

While SAW devices often have all of their contacts on the top surface, most of the other devices have contacts on both the bottom and the top of the piezoelectric element, so that the AlN element is often deposited on top of the bottom electrode, which is usually a metal. The metals often considered are Al for room-T applications and Pt for high-T applications. For the case of SAW devices, AlN films have also been grown on single-crystal sapphire with the growth plane being parallel to the (0001) sapphire plane.³³ The growth procedure for the deposition of AlN on amorphous SiO₂ was optimized by varying the deposition parameters such as process pressure, gas mixture, substrate temperature, and discharge power to optimize the structural properties of AlN. It was found that the best film texture was obtained for a particular set of parameters: a process pressure of 4 mTorr, gas mixture of 25% Ar and 75% N₂, substrate temperature of 350 °C, and discharge power of 350 W.³² Growth on the metal electrodes and single-crystal sapphire was optimized in the same way.

High-quality, single-crystal films cannot be grown at these low temperatures, because the atoms are unable to reach their equilibrium position. The focus therefore is to try to grow highly textured films with the piezoelectric preferred plane in the grain being parallel to the growth plane. Another way of saying the same thing is that the plane normal is perpendicular to the growth plane. If all of the crystallites are aligned with the c -axis, there should be virtually no effect on the magnitude of d_{33} . The fact that it is reduced approximately 20% compared to the value for a single crystal is, in part, due to the small disorientations.³⁴ The disorientation do to the rotation of the crystallites about the c -axis should have no effect on d_{33} , but pictorially it should have an effect on d_{31} . This is because the 1-directions in each of the crystallites will be rotated relative to each other. However, since the magnitude of d_{31} is the same in any direction lying in the (0001) plane, changing the 1-direction should have little to no effect on its magnitude.

The method often used to determine how well the crystallites are oriented parallel to the c -axis is to measure the peak width of the (0002) X-ray rocking curve peak. The measured peak width is the FWHM intensity. The more perfectly the c -axes of the crystallites are aligned, the narrower the peak is. For the sputtered AlN films discussed previously, the value measured was $\text{FWHM} = 1.6^\circ$.

Surface wave devices do not have bottom electrodes, so there are fewer constraints on what the substrate is. Sapphire single crystals are attractive because high-quality, low-price single crystals are readily available and the crystal structure is similar to that of AlN. The growth surface for the sputtered AlN films is parallel to the (0001) plane.³⁵ The orientation of the substrate is important because the AlN films tend to grow epitaxially. That is, the atoms in the growing film attempt to replicate the structure of the substrate. The films exhibited a (0001) AlN// (0001) sapphire plane orientation. The in-plane orientation was $[2\bar{1}10]$ AlN// $[1\bar{1}00]$ sapphire corresponding to a rotation of 30° of the $[2\bar{1}10]$ AlN direction about the c -axis. This rotation is thought to be favored because the crystal structures are slightly different, and the length of the hexagonal lattice parameters that lie in the (0001) planes are quite different. This tendency for the atoms in the film to attempt to align with the atoms in the substrate improves the alignment of the columnar AlN grains with the c -axis, this is reflected in the film having an (0002) rocking curve FWHM value of about 0.4° .

Also, the growth temperature is no longer confined and films of even higher quality can be grown by MOCVD on sapphire³⁶ single crystals at approximately 1150°C . Films had (0002) peak widths of $123''$ (arcsec), which equals 0.034° . There often is an interest of people who work on electronic devices to quantify the rotation of the crystallites about the c -axis; this is done by measuring the peak width of a pyramidal plane. They used the $(10\bar{1}2)$ reflection and found the peak width to be $592'' = 0.164^\circ$. This might be of interest to those making SAW devices, because the small angle grain boundaries created by these rotations can scatter the surface sound waves. However, the effect is expected to be small. AlN films have also been grown on single-crystal SiC substrates.³⁷ The rocking curve widths were $123''$ for the (0002) reflection and $304''$ for the $(20\bar{2}1)$. It is likely that the pyramidal peak width for the SiC substrate was a little smaller, because the a lattice constants of SiC and AlN are more similar. The most pristine films that can be grown are AlN films grown homoepitaxially by MOCVD on high-quality AlN substrates because the crystal structure is identical and there is no lattice mismatch. The (0002) peak width was $25'' = 0.007^\circ$.³⁷

6.3.4 Conclusion

There are needs to monitor systems that operate at high temperatures in a harsh environment, where harsh environments include chemical such as oxidizing environments and nuclear such as the high-energy nuclear particles found in nuclear reactors. One example is the use of a sensor to monitor the pressure changes in the turbine chambers of jet airplanes by measuring the change in charge on the piezoelectric element created by the change in pressure in the chamber. A pressure change is an indicator for system degradation, and in extreme cases, failure. Immediate attention keeps the plane operating at peak performance, and the lack of any indication of degradation extends the time between routine maintenance.

Another example is to use a sensor to monitor the temperature changes inside a nuclear reactor by measuring the speed of sound of the sound waves created by a vibrating piezoelectric element as a temperature change is an indicator for system degradation, and in extreme cases, failure. This sensor would replace thermopiles that only measure the temperature in the immediate surrounding area as opposed to sampling the entire area as the sensor does. Immediate attention keeps the nuclear reactor operating at peak performance, and the lack of any indication of degradation extends the time between routine maintenance.

Using a sensor to monitor changes in the structure and microstructure of metal tubing carrying very hot liquids by recording cracks and changes in the microstructure of the steel tubing through an analysis of the reflected waves can lead to immediate repair and prevention of a disaster. An array of individual sensors can monitor these defects in more detail as they would essentially act like an ultrasonic imager. One could also construct the imager as a MEMS. This is usually the better approach because the individual devices are closer together and will have more similar characteristics, and both of these attributes will improve the quality of the image. The resonant frequency of the individual devices can also be better controlled, because it is controlled by the geometry of the element, not the speed of sound in the piezoelectric element. MEMS can also be developed to expand the capabilities of ICs that provide power to the MEMS sensors, and in some cases, replace some electronic devices with equivalent piezoelectric devices that perform better at the higher temperatures. One example is an ultrasonic resonator acting as a switch, which is what a transistor sometimes does.

To be able to do this, one must find a piezoelectric element that can withstand the high temperature and harsh environmental conditions. Of the popular piezoelectric materials AlN, ZnO, SiO₂, GaPO₄, and LGS, and the ferroelectrics, LiNbO₃ and PZT, only AlN and LGS are both piezoelectric and chemically stable at the higher temperatures, 800–1200 °C. AlN does begin to oxidize at 800 °C, but the thin oxide

created on it protects it until the temperature T reaches $1370\text{ }^{\circ}\text{C}$. LGS becomes ionically conductive and also quite lossy when $T > 1000\text{ }^{\circ}\text{C}$. PZT ceases to be ferroelectric before T reaches $400\text{ }^{\circ}\text{C}$, α -quartz transforms to β -quartz at $573\text{ }^{\circ}\text{C}$, and GaPO_4 transforms to another phase at $970\text{ }^{\circ}\text{C}$; and neither of the high-temperature phases are piezoelectric. Also, the piezoelectric phase becomes quite lossy $200\text{ }^{\circ}\text{C}$ below their transition temperature. ZnO and LiNbO_3 preferentially lose oxygen and become lossy at $T < 500\text{ }^{\circ}\text{C}$.

Of the two primary materials, LGS and AlN , only AlN has been tested in a nuclear environment, and it was shown to be more resilient than the other piezoelectric materials tested with it. Comparing the piezoelectric properties, LGS has an electromechanical coupling coefficient, k_{eff}^2 , that is more than twice as large as it is for AlN . This is probably the most important factor. However, AlN has less loss as shown by its smaller $\tan\delta$ and it is more resistive. It also has larger elastic constants that enable higher-frequency operation everything else being equal.

Individual devices use wafers cut from bulk single crystals as the active piezoelectric element. AlN bulk single crystals have only recently become available and are very expensive so availability is very small if it even exists. Highly textured films with the required (0001) orientation are inexpensive and available, but they are more complex than a wafer. On the other hand, bulk LGS single crystals and wafers cut from them are readily available. Single-crystal or highly textured AlN films with the required orientation deposited in a layered structure with a bottom and top electrode can quite easily be created and can be deposited over a large temperature range onto a number of different substrates. There have been suggestions that LGS films can be deposited with the required stoichiometry using pulsed laser ablation, but the process does not yet appear to be refined enough to use yet.

In the case of MEMS, a substrate is required that is compatible with the piezoelectric element grown on it, as well as being able to withstand the high-temperature conditions. Si is the substrate of choice because the MEMS could be integrated with the electronics to power them but the Si-based IC elements can operate only for $T \leq 500\text{ }^{\circ}\text{C}$. Good-quality, highly textured AlN films with the required (0001) orientation can be deposited on it at $T < 500\text{ }^{\circ}\text{C}$; AlN is said to be CMOS compatible. For $T > 500\text{ }^{\circ}\text{C}$, Si becomes reactive, but it can be replaced by an α -SiC film deposited on it or by the single-crystal wafer. SiC is stable up to at least $1500\text{ }^{\circ}\text{C}$.

Electrodes that can withstand the high temperatures are also required. Pt with a Ti adhesion promoter is the metallic electrode of choice primarily because it does not oxidize for $T < 1100\text{ }^{\circ}\text{C}$. However, Pt electrodes with the desired thickness of

100 nm fail when $T > 700\text{ }^{\circ}\text{C}$ by the process of agglomeration whereby this thin layer with a large surface to thickness ratio alters its microstructure through the process of grain growth. This causes larger and thicker, but physically disconnected, grains to form. The temperature at which this process kicks in can be raised by increasing the layer thickness. Sealing the electrode with a 25-nm ceramic coating such as SiAlON raises the agglomeration T of the 100- μm film to $900\text{ }^{\circ}\text{C}$. Adding 10% Rh to the Pt and utilizing the 25-nm SiAlON ceramic coating increases the agglomeration T to over $1000\text{ }^{\circ}\text{C}$.

With its unfilled d -electron shell in the Ti atom, TiN is an alternative non-metallic electrode material. Its resistivity can be as low as $13\text{ }\mu\Omega\cdot\text{cm}$, which is only approximately $2\text{ }\mu\Omega\cdot\text{cm}$ larger than that of Pt. However, this value is very difficult to achieve, because it is so sensitive to the grain size, which is usually much too small— $100\text{ }\mu\Omega\cdot\text{cm}$ is a more likely value. TiN also oxidizes rapidly for $T > 600\text{ }^{\circ}\text{C}$. It should, however, be possible to raise this temperature a few hundred degrees by utilizing a 25-nm SiAlON ceramic coating.

Heavily n -type doped SiC 300-nm-thick and LSM electrodes have been explored, but each resistivity is too high, greater than $1000\text{ }\mu\Omega\cdot\text{cm}$, and for LSM, this is the value at $900\text{ }^{\circ}\text{C}$, and increases exponentially as T decreases. SiC has the advantage of being stable up to at least $1500\text{ }^{\circ}\text{C}$ if it has a coating that prevents it from oxidizing.

6.3.5 References

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7. Conclusion

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7.1 Ga₂O₃

7.1.1 Introduction

β -Ga₂O₃ has an indirect bandgap of $E_G = 4.84$ eV with a direct gap only 0.29 eV larger. It is a unipolar n-type semiconductor currently with a maximum electron mobility of approximately 200 cm²/V·s, its E_D for the donors Si and Sn ranges from 16–50 and 7–60 meV, and the controllable doping level range for each is 10¹⁶–10²⁰ cm⁻³. Further, it has a primary thermal conductivity of 10–30 W/mK and a monoclinic crystal structure with the (010) plane being the usual homoepitaxial growth plane.

Given that β -Ga₂O₃ is monoclinic, the plane on and the direction in which the measurements are made should be listed. For example, the room-temperature static relative dielectric constant, ϵ_r , perpendicular to the planes (100), (010), and (001) are 10.2 ± 0.2 , 10.87 ± 0.08 , and 12.4 ± 0.4 , respectively.¹ One of its most significant advantages is that good-quality single crystals can be easily grown in large volumes at reasonable prices using a number of melt-growth techniques.

7.1.2 Optical Devices

Ga₂O₃ is an intrinsically suitable material for being used in deep UV, solar-blind photodetectors because of its large E_G , which corresponds to a photon with a wavelength in the range of 250–280 nm. This is a good match for solar-blind detection, which is the region of wavelengths of 200–280 nm, where signals located within this spectral region can be detected efficiently without being influenced by radiation from the sun. Applications include ozone holes monitoring, flame detection, space communications, missile guidance, and biochemical detection.

The photodetectors are mainly based on two structures: metal–semiconductor–metal (MSM) and the Schottky diode. MSM devices have the advantages of easy fabrication and integration, and their performances are dependent on the size of the interdigital electrodes. Schottky diodes have high response speeds and high rejection ratios. Different kinds of metals have been used to form Schottky contacts. The device performance is also dependent on the quality of the material. Much more work needs to be done to improve the responsivity, EQE, and response speed at the same time. The inability to be able to dope the Ga₂O₃ p-type is still a severe problem, and the severe persistent photoconductivity, which is common in oxides with their complicated defect structures, needs to be addressed.²

7.1.3 High-Power Electronic Devices

Ga₂O₃ is emerging as a viable candidate for certain classes of power electronics with capabilities beyond existing technologies due to its large bandgap and the availability of large-diameter, relatively inexpensive substrates.³ In theory, devices made from it should be able to handle 10 times as much power as current SiC devices and could enable them to be a realistic alternative to traveling wave tube (TWT) devices for the low end of the frequency spectrum. The initial thrust is targeted toward high-power converters for both DC–DC and DC–AC applications, and Schottky diodes could supplement 600-V Si or SiC rectifiers targeted at switch mode power converters. Under normal circumstances, a pn diode would be preferred, because it has fewer interfacial defects and a larger turn-on voltage, but, as noted previously, Ga₂O₃ cannot be made p-type. It may be possible to use heterojunction structures involving other oxides that are p-type. At this stage, however, this approach has not yielded high-quality heterojunctions.

The attraction of Ga₂O₃ for high-power, two-terminal devices is its large E_G and the associated large critical electric field, ξ_c , and breakdown voltage, V_{BR} . Even with its relatively small electron mobility, μ_e , of approximately 200 cm²/V·s, the maximum carrier concentration it can be doped with, n_{max} , for a given V_{BR} is larger because it is proportional to $\mu_e \xi_c$.³ Thus, the specific on resistance, R_{ON} , can be smaller, so there is less loss for a given V_{BR} . This would enable one to make a more-efficient device if the loss is determined by the forward switching loss. Another way to look at this is that if the minimum controlled donor density, n_{min} , is the same, the semiconductor with the larger ξ_c will have the larger V_{BR} and will therefore be able to handle more power.

The intentional n-type dopants, Si, Ge, and Sn, appear to be effective-mass-like shallow donors without any peculiarity such as DX behavior. The background carrier concentration is often reported as being approximately 10¹⁶ cm⁻³, and it is believed to be mostly Si. If it turns out to be difficult to achieve a lower background doping concentration, then Ga₂O₃ will lose its potential advantage for higher-power applications over SiC because SiC can be controllably doped in the low 10¹⁴ cm⁻³ range. It seems more likely that the intrinsic point defects will be the larger problem, especially since the complicated monoclinic unit cell contains four Ga₂O₃ units and there are two different Ga sites and three different O sites, and O vacancies can be shallow donors and are likely to be the most prevalent.⁴

Intrinsic defects are also thought to be responsible for a number of deep states in Ga₂O₃. Currently, all rectifiers show performance limited by their presence, as breakdown is often initiated in the depletion region. Breakdown also occurs prematurely near the electrode corners. There are a number of common edge

termination techniques, the most common being field plate edge termination, which uses an extension of the Schottky metal over a dielectric layer at the edge to improve the reverse blocking capability. Other approaches such as p-guard rings or junction termination extension are not possible in Ga₂O₃ due to the lack of p-type doping capability and require the use of other p-type oxides integrated into the structure.

The identification of the physical origins of the deep-level states is an important task, because they are also associated with leakage currents in power devices and may also be associated with the long delay times and persistent photoconductivity often observed in solar-blind photodetectors. Larger leakage currents are often associated with dislocations, but with its complex crystal structure, the formation energy of dislocations is very high so their concentration is usually low—often approximately 10^3 cm^{-2} . Therefore, it is unlikely they are a major contributor to the leakage current unless the effect of an individual dislocation is very large.

Given the unipolar nature of Ga₂O₃, FETs with Schottky gates are currently the transistors of choice. The yet-to-be-answered question is whether the voltages where the premature breakdown that occurs by using a metal gate are large enough to enable the device to take advantage of the potentially larger critical field made possible by the larger E_g . Another possibility is to determine if p-type heterojunctions composed of p-type ternaries with sufficient solubility formed by substituting Al and/or In for some of the Ga can be created and successfully deposited.

Even if the ternary cannot be made p-type, the heterostructure could be used to create a HEMT. This has been achieved using the alloy [Al_xGa_(1-x)]₂O₃ to a remarkable value of $x = 0.65$ with a tunable bandgap value ranging from 4.9 to 5.8 eV. It has only been achieved by MBE; achieving this by using other growth techniques such as MOCVD or PLD and the demonstration of modulation-doped devices remains to be explored. It is predicted that the 2DEG at the interface will be able to screen out certain phonon modes and a mobility of approximately $500 \text{ cm}^2/\text{V}\cdot\text{s}$ can be achieved. For bulk crystals, the ternary retains the monoclinic crystal structure up to $x = 0.80$. The difficulty of dealing with the mismatch stress will be a challenge. Given the complexity of the unit cell, it is unlikely that the stress can be relieved by the formation of dislocations, so the mismatch stress will become internal stress, which could lead to bowing and cracking.

The lack of p-type doping in Ga₂O₃ means that vertical transistor structures such as the current aperture vertical electron transistor (CAVET), attractive due to inexpensive large-area commercial native substrates, have to rely on current channels confined using either implanted current blocking layers, essential for

being able to pinch off the HEMT channel at the top of the structure. The fin field-effect transistor (FINFET) could be used to replace the CAVET if a current blocking layer cannot be created.

There are significant challenges for Ga₂O₃ MOSFETs in finding an application space not currently filled by SiC devices. To do so, Ga₂O₃ must offer performance characteristics that are currently not possible using any of the UWBG materials. SiC MOSFETs have found application in fast, high-voltage power converters due to their superior system efficiency, which can be tracked back to the fundamental properties of SiC: WBG, high critical field, long (μ s) minority carrier lifetime, and being ambipolar.

It is conceivable that given the extreme radiation hardness of this material, combined with thermal stability and high power, it could offer stable device operation in the most extreme environments known, such as deep space. Single event burnout due to heavy ion damage is a big problem for SiC MOSFETs in particular, where it has been linked to the parasitic BJT formed between the source, channel, and drain epilayer. This is because acceptors in Ga₂O₃ are not expected to ionize sufficiently to enable controllable p-type doping in this material. However, the WBG of Ga₂O₃ means there are limited choices to obtain sufficient band offsets with the dielectric.

The thermal conductivity of Ga₂O₃ is very low, possibly because of the presence of unintentional defects such as the Ga vacancies. Consequently, diamond-based heat spreader technology, such as that developed for GaN, will be needed; the self-heating effects must be mitigated in order to utilize Ga₂O₃ devices for high power at even moderate switching frequencies. This could be done by transferring devices to another substrate such as diamond or thinning down the substrate and using a heatsink as well as top-side heat extraction.

7.1.4 RF Electronics

β -Ga₂O₃ presents improved RF and power switching metrics compared with other WBG materials. It also has a larger HCAFOM ($\epsilon\mu^{0.5}E_c^2$) than GaN, which translates into lower manufacturing costs. Promising progress has also been made on RF Ga₂O₃ devices that demonstrated record-high $f_{\max}$ of 17.1 GHz, as well as $P_{\text{out}} = 0.25$ W/mm and PAE = 15% at 1 GHz under class AB operation and a $P_{\text{OUT-MAX}}$ of 530 mW/mm. Future device performance will benefit from MBE grown layers, heterostructure designs, removal of parasitic losses by scaling, field management with implant and field plate, and thermal engineering.

7.2. AlGaN

7.2.1 Introduction

AlGaN is a complete solid solution whose properties vary with the composition, has a direct E_G over the complete range of Al concentration, and it continuously increases with the %Al from 3.43 to 6.2 eV at room temperature. It is a bipolar semiconductor with a low-doped maximum electron mobility of $1400 \text{ cm}^2/\text{V}\cdot\text{s}$ for 0% Al, and a minimum value of 27 for 64% Al and 425 for AlN.⁵ E_D for the primary donor, Si, increases slowly with the %Al from approximately 20 meV for 0% Al to approximately 75 at approximately 85% Al; it drops off precipitously after that because the Si donor becomes a DX center. The small hole mobility— $24 \text{ cm}^2/\text{V}\cdot\text{s}$ for GaN—is not a big issue because most of the bipolar junctions are p+n junctions. The more serious issue is that for GaN, $E_A \approx 200 \text{ meV}$ and it increases with %Al making hole activation at room temperature challenging to impossible. The sample can be controllably doped n-type at 10^{16} to mid- 10^{19} cm^{-3} . It is difficult to controllably dope below 10^{16} cm^{-3} , because for all types of growth, this is the usual background contamination for O and Si. From MOCVD growth, the background concentration of C, an acceptor under normal conditions, created by the decomposition of the organometallic at the high growth temperatures required for the growth of AlGaN, is typically greater than 10^{16} cm^{-3} . Controllable doping at mid- 10^{15} cm^{-3} has been achieved in HVPE GaN by eliminating all quartz fixtures in the growth zone and C concentrations have been reduced to the low 10^{15} cm^{-3} region by growing at very high V/III ratios.

These efforts will have to be refined and reduced in cost for AlGaN to be competitive with SiC high-voltage devices. AlGaN has a low thermal conductivity due to alloy scattering, but the device structure can be grown on AlN or SiC, which do have good thermal conductivities, so that transferring fabricated devices to a high thermal conductivity substrate will not be required. AlGaN has the hexagonal wurtzite structure for all Al concentrations, and the Ga-rich (0001) surface is the preferred growth surface. This is a great benefit to the electronic devices, because it produces device structures with the largest polarization charges. Optical devices prefer little or no polarization charge because the polarization field separates electrons and holes thereby reducing their recombination efficiency. Thus, nonpolar or semi-polar planes are preferred.

With its relatively large piezoelectric constants, large sound velocities, large electrical resistance, and small loss tangent, AlN has been used for many types of piezoelectric devices that operate at room temperature. Now, it is being considered for use in individual sensors collectively in MEMS operating at higher temperatures and/or caustic environments, because it is chemically quite stable and also quite

radiation hard. GaN single crystals can be grown with good structural quality using the ammonothermal method, but they cannot be controllably doped, as they contain a larger concentration of Si; they also are expensive. AlN single crystals with high structural quality have been grown by physical vapor transport, but they cannot be controllably doped because impurities and/or point defects make them insulating. They are also expensive. The AlGaIn grown on either GaN or AlN single-crystal substrates will have to compensate for the lattice mismatch by forming dislocations or become highly stressed.

7.2.2 Optical Devices

Broadband applications include air/water/surface/food purification-disinfection, materials and polymer processing/curing, medical/biomedical diagnostics and treatment, and scientific instrumentation. The EQE for AlGaIn LEDs moderately decreases with wavelength starting at approximately 25% with GaN (360 nm) but drops off precipitously at wavelengths below 250 nm. The notable exception is for LEDs near 270 nm with 10% EQE, where significant investment has been made to address germicidal applications such as water purification and fluorescence detection of biomolecules. This has enabled the surface disinfection market to grow dramatically since the COVID-19 pandemic burst onto the world stage in early 2020. This has dramatically increased demand for UV-C LEDs. Many companies are now selling products that incorporate them to disinfect masks and other personal protective equipment and medical equipment.

The EQE of UV-C LEDs emitting at 235 nm has been increased by improving the structural quality of the device structure by growing the AlGaIn on high-quality AlN substrates instead of sapphire. This significantly reduces the dislocation concentration, which reduces the loss due to nonradiative recombination. More importantly, the wall plug efficiencies are much better because of the lower operating voltages that can be utilized and the lifetimes are long enough to allow practical applications.⁶

Unintentional point defects can also reduce the EQE by absorbing the light before it escapes as is indicated by the transparency of the AlN. Since current UV-C LED production uses a flip-chip approach, where the radiation is extracted through the substrate, the transparency of the AlN substrates is a key parameter. Oxygen and probably carbon are primary sources, as reducing their concentrations increases the transparency.⁷

Narrowband photons, those that are more precisely tailored and coherent, are used for point-of-need identification of bio-chemicals by Raman spectroscopies, non-line-of-sight communication, or resonant interaction with specific atomic

absorption lines of interest to sensing precisely defined transitions for quantum information processing scheme. Asahi Kasei, Crystal IS, and Nagoya University succeeded in making the world's first UV-C laser diode.⁵ There were two key developments that enabled this accomplishment. One was the realization of very high-quality pseudomorphic AlGa_N layers by growing the device structures on high-quality AlN substrates, and the other was development of hole injection by using a graded, undoped Al_{1-x}Ga_xN layer that was used to conduct holes from the p-type GaN contact.

The incremental improvements noted above points toward being able to combine all of these functions on a single chip in the form of PICs operating in the UV and visible spectral bands. Several recent studies have explored the implementation of AlN for on-chip optical waveguides and microresonators and its potential benefits.⁸ The desirable properties of AlN include UWB (~6.0 eV), a wide spectral window of optical transparency (0.21 to 13.6 μm), excellent nonlinear optical properties including electric susceptibilities χ^2 and χ^3 , a high thermal conductivity (285 W/m-K), and high radiation tolerance.

7.2.3 RF and High-Power Electronic Devices

GaN/AlGa_N heterostructure HEMTs have been used in the RF space for years and are ubiquitous with applications ranging from radar to cell phones. There is a strong interest in replacing the high-power, large-bandwidth TWT amplifiers that radar commonly uses. GaN HEMTs eliminate the inherent TWT amplifier limitations of relatively short operating life due to cathode exhaustion, risk of TWT damage at turn-on after extended storage, and shorter mean time between failure because of all components in the tube being potential single points of hard failure. At the heart of most GaN HEMT-based radar designs is a pulsed amplifier that uses a pulsed RF signal, with the transistor being powered by a DC bias. Pulsing the DC bias as well for some applications reduces both interference and power consumption. Pulsed operation, as opposed to the CW mode, has the advantage of reducing external DC power needs and heat generation. However, TWTs can handle significantly more power than GaN HEMTs can.

As noted in the Introduction, Al_xGa_(1-x)N/Al_yGa_(1-y)N HEMTs would have much smaller mobilities caused by alloy scattering, and their FOM would be less than that of GaN for the smaller Al concentrations, but they are equal when the Al content is 72%. The differential increases rapidly with x after that as both the energy gap and the electron mobility increase⁵ so Al_xGa_(1-x)N/Al_yGa_(1-y)N HEMTs theoretically have greater potential to replace the TWTs. This issue is less of a problem for high-frequency HEMTs, where the speed is determined by the

saturation velocity, which is independent of the electric field, and not by the mobility.⁹

Heterostructure GaN power transistors are starting to find niche applications in 600-V market segments such as data center server power supplies, especially if the substrate is Si, for reasons of cost and compatibility. However, for very-high-voltage applications, which are the niche for UWBG semiconductor devices, a lateral device structure is not the structure of choice because the device would consume too much of the valuable surface area, and surfaces are prone to having defects that cause premature breakdown.

In addition to the materials problem associated with GaN—the larger unintentional background carrier concentration and the inability to locally dope the material p-type using ion implantation—the compressive mismatch strain in the AlGaIn device structure grown on the high-quality AlN substrate will have to be compensated for to some extent by mismatch dislocations.¹⁰ Further, the dislocations will have to primarily be basal plane dislocations, as opposed to the threading dislocations that usually form¹¹ and penetrate to the high-field regions in the device structure where they can cause premature breakdown. In addition, the drain contacts will have to be made on the top side of the device because the AlN substrate will be an insulator.

7.2.4 High Operating Temperature Piezoelectric Sensors and Sensor Systems

There are needs to monitor systems that operate at high temperatures in a harsh environment such as oxidizing environments and nuclear reactors. One example is using a sensor to monitor the pressure changes in the turbine chambers of jet airplanes by measuring the change in charge on the piezoelectric element created by the change in pressure in the chamber. A pressure change is an indicator of system degradation, and in extreme cases, failure. Another example is using a sensor to monitor the temperature changes inside a nuclear reactor by measuring the temperature-dependent speed of sound of the sound waves created by a vibrating piezoelectric element. A temperature change is an indicator of system degradation, and in extreme cases, failure.

A sensor can be used to monitor changes in the microstructure of metal tubing carrying very hot liquids by recording cracks and changes in the microstructure of the steel tubing by analyzing the reflected waves. An array of individual sensors can monitor these defects in more detail, as they would essentially act like an ultrasonic imager. One could also construct the imager as MEMS.¹² This is usually the better approach, because the individual devices are closer together and will have more similar characteristics, and both of these attributes will improve the quality of

the image. The resonant frequency of the individual devices can also be better controlled, because it is controlled by the geometry of the element, not the speed of sound in the piezoelectric element. MEMS can also be developed to expand the capabilities of ICs that provide power to the MEMS sensors, and in some cases, replace some electronic devices with equivalent piezoelectric devices that perform better at the higher temperatures. One example is an ultrasonic resonator acting as a switch, which is what a transistor sometimes does.

To be able to do this, one must find a piezoelectric element that can withstand the high temperature and harsh environmental conditions. Of the popular piezoelectric materials, AlN¹³ and LGS are the only piezoelectric materials that are both piezoelectric and chemically stable at the higher temperatures, 800–1200 °C. AlN does begin to oxidize at 800 °C, but the thin oxide created on it protects it until the temperature, T , reaches 1370 °C. LGS becomes ionically conductive and also quite lossy when $T > 1000$ °C. Of the two primary materials LGS and AlN, only AlN has been tested in a nuclear environment, and it was shown to be more resilient than the other piezoelectric materials tested with it. Comparing the piezoelectric properties, LGS has an electromechanical coupling coefficient, k_{eff} ,² which is more than twice as large as it is for AlN. However, AlN has a smaller $\tan\delta$ and is more resistive. It also has larger elastic constants that enable higher frequency operation everything else being equal.

Individual devices that have both front and back contacts use wafers cut from bulk single crystals as the active piezoelectric element. AlN bulk single crystals have only recently become available and are very expensive, so availability is very small, if it even exists. On the other hand, bulk LGS single crystals and wafers cut from them are readily available. However, highly textured films with the required (0001) orientation, which are inexpensive and available, can be used for surface wave devices, and microdevices with front and back side contacts can be fabricated on them. Single-crystal or highly textured AlN films with the required orientation deposited in a layered structure with a bottom and top electrode can quite easily be created, and they can be deposited over a large temperature range onto a number of different substrates. There have been suggestions that LGS films can be deposited with the required stoichiometry using pulsed laser ablation, but the process does not yet appear to be refined enough to use them yet.

In the case of MEMS, a substrate is required that is compatible with the piezoelectric element grown on it, as well as able to withstand the high-temperature conditions. Si is the substrate of choice, because the MEMS could be integrated with the electronics to power them, but the Si-based IC elements can operate only for $T \leq 500$ °C. Good-quality, highly textured AlN films with the required (0001) orientation can be deposited on it at $T < 500$ °C; AlN is said to be CMOS

compatible. For $T > 500\text{ }^{\circ}\text{C}$, Si becomes reactive, but it can be replaced by an α -SiC film deposited on it or by the single-crystal wafer. SiC is stable up to at least $1500\text{ }^{\circ}\text{C}$.

Electrodes that can withstand the high temperatures are also required. Pt with a Ti adhesion promoter is the metallic electrode of choice primarily because it does not oxidize for $T < 1100\text{ }^{\circ}\text{C}$.¹⁴ However, Pt electrodes with the desired thickness of $100\text{ }\mu\text{m}$ fail when $T > 700\text{ }^{\circ}\text{C}$ by the process of agglomeration, whereby this thin layer with a large surface-to-thickness ratio alters its microstructure through the process of grain growth. This causes larger and thicker, but physically disconnected, grains to form. The temperature at which this process kicks in can be raised by increasing the layer thickness. Sealing the electrode with a 25-nm ceramic coating such as SiAlON raises the agglomeration T of the $100\text{-}\mu\text{m}$ film to $900\text{ }^{\circ}\text{C}$. Adding 10% Rh to the Pt and utilizing the 25-nm SiAlON ceramic coating increases the agglomeration T to over $1000\text{ }^{\circ}\text{C}$.

With its unfilled d-electron shell in the Ti atom, TiN is an alternative nonmetallic electrode material.¹⁵ Its resistivity can be as low as $13\text{ }\mu\Omega\cdot\text{cm}$, which is only approximately $2\text{ }\mu\Omega\cdot\text{cm}$ larger than that of Pt. However, this value is very difficult to achieve, because it is so sensitive to the grain size, which is usually much too small, so $100\text{ }\mu\Omega\cdot\text{cm}$ is a more likely value. TiN also oxidizes rapidly for $T > 600\text{ }^{\circ}\text{C}$. It should, however, be possible to raise this temperature a few hundred degrees by utilizing a 25-nm SiAlON ceramic coating.

Heavily n-type doped SiC 300-nm-thick and LSM electrodes have been explored, but each of their resistivities is too high, greater than $1000\text{ }\mu\Omega\cdot\text{cm}$, and for LSM, this is the value at $900\text{ }^{\circ}\text{C}$ and increases exponentially as T decreases. SiC has the advantage of being stable up to at least $1500\text{ }^{\circ}\text{C}$ if it has a coating that prevents it from oxidizing.

7.3 Diamond

7.3.1 Introduction

Diamond has an indirect bandgap of $E_G = 5.5\text{ eV}$; the large E_G is a direct result of the very strong covalent bond, which also contributes to being very radiation hard. Diamond is also a bipolar semiconductor with a maximum low doped electron mobility of greater than $1800\text{ cm}^2/\text{V}\cdot\text{s}$ and a maximum low doped hole mobility of greater than $2000\text{ cm}^2/\text{V}\cdot\text{s}$.¹⁶ The E_D for P, the current primary donor, is 570 meV , and the E_A for B, the current primary acceptor, is 360 meV . The controllable doping level range has a different type of important issue for diamond, because it has to be heavily doped to create donor and acceptor bands, thereby enabling hopping

conduction that reduces the effective E_D to 55 meV and E_A to 40 meV. The P concentration has to be controlled in the 10^{16} cm^{-3} range when it is used in a Schottky np diode so that the n-region can be completely depleted during device operation.^{16–18} Care is also taken to limit the amount of N contamination in material used for electronic devices because, being a deep donor ($E_D = 1700 \text{ meV}$), it can compensate the B. However, it is a welcome species when the material is used for quantum computing, as it can controllably form N-C vacancy complexes using radiation followed by an anneal.

Diamond has the diamond cubic structure, and the usual homoepitaxial growth planes are the (001) and (111) with the (001) plane producing better structural quality and the (111) plane incorporating P better.¹⁶ Very-high-quality diamond single crystals can be grown by the high power high temperature (HPHT) method, but they are typically only 3–10 mm on a side, and it is unlikely they can be grown much larger than that.¹⁶ While probably being adequate for the creation of RF devices, the diamond substrates that are usually used are probably not good enough for creating high-power electronic (HPE) devices. They are formed by growing microwave plasma-enhanced CVD diamond films on an iridium film that was grown on a yttrium-stabilized zirconia layer deposited on a (001) oriented Si wafer. This film is a highly (001) textured film composed of domains about 1 μm in diameter that generate (001) and (311) rocking curves with $230''$ and $430''$ half widths,¹⁹ respectively. The structural quality of these films is similar to that of GaN films grown on SiC or sapphire and the dislocation concentrations are similar— 10^7 to 10^9 cm^{-2} . Diamond also has unusual surface properties that can be exploited such as the ability to adsorb a monolayer of H that can be used to create a 2DHG.²⁰ Diamond has the best room-temperature thermal conductivity, which is 2300 W/mK. This, along with having both donors and acceptors each having a relatively high mobility are its most significant advantages.

7.3.2 Electronic Diodes

7.3.2.1 Schottky NP Diodes

Diamond has an indirect bandgap so the recombination times, and therefore the diffusion lengths, are longer, which enables many carriers to be able to tunnel through thin layers. This ability is exploited in the operation of a Schottky np diode (SNPD). The top layer is the Schottky metal contact, and the next layer is the n-layer that has the combination of being thin and low doped, so that is totally depleted by its junction potentials when no voltage is being applied.^{16–18} The SNPD therefore will not have to deal with the donor and its large E_D and will have the benefit of the smaller effective E_A because the p-layer can be heavily doped. It can

be constructed as a true vertical device if the p-layer is a heavily doped substrate, and will have a smaller turn-on voltage because the hole barrier height is smaller than the electron barrier height.¹⁶ It will also be able to switch faster because it acts like a unipolar device¹⁸ and will have a larger breakdown voltage than a traditional Schottky diode because the electric field is more spread out by the depleted n-layer.¹⁸ It appears that it could possibly compete with the SiC junction barrier Schottky (JBS) diode in the HPHF regime.

7.3.2.2 PiN Diodes

The PiN diode^{16,21} differs from the SNPD in that the top layer is an ohmic contact and the next layer is a thin ($\sim 0.5 \mu\text{m}$), heavily p-doped n-layer ($\sim 5 \times 10^{19} \text{ cm}^{-3}$) that does not get depleted under bias, and the heavily doped ($\sim 10^{20} \text{ cm}^{-3}$) p-layers are approximately $10 \mu\text{m}$ thick. In the device discussed in the following, the undoped i-layer was doped approximately 10^{16} cm^{-3} and had a thickness of 0.5 or $8.5 \mu\text{m}$. The current density was approximately 60 A/cm^2 at 20 V or approximately 6 A/cm^2 at 10 V ; the blocking voltage was 207 or 1040 V . This illustrates that the determining factor is the thickness of the i-layer—the thicker the layer, the larger the blocking voltage because the electric field is extended over a greater length, but the current is smaller because the injected minority carriers have a longer distance over which they can recombine.

This geometry is very different from the geometry of the p+n- diode, where the on-resistance is determined by the doping level of the n-layer and how thick the depletion layer is at breakdown. The BFOM is determined using the latter, so it is not appropriate to include diamond diodes in the $R_{\text{SP-ON}}$ versus V_{B} that are so frequently used. It also explains why a diamond PIN diode can maintain an electric field of 3.9 MV/cm and only have a blocking voltage of 1040 V .²¹ A SiC PiN diode could likely have a $V_{\text{BR}} > 10 \text{ KV}$ while maintaining an electric field half as large, because the electric field can be extended over a layer greater than $100 \mu\text{m}$ that can be controllably doped at a concentration of approximately $5 \times 10^{14} \text{ cm}^{-3}$ over a thickness this large. Thus, it is likely that diamond PiN diodes should focus on the HPE application area where $V \leq 3 \text{ KV}$.

7.3.2.3 Schottky and NP Diodes

Schottky diodes are also available, but they should be fabricated on heavily doped p-type material if they are going to be able to carry considerable current at room temperature. At this high level of doping, the leakage currents tend to be larger and are prone to cause premature breakdown. This to some extent be ameliorated by having a thin lower p-doped layer in contact with the Schottky metal.¹⁶

Due to its very strong σ -bonds, its small size, its small atomic spacing, and not being the stable phase, creating an np diode has not been a straightforward process. The acceptor of choice, B, can more easily substitutionally replace a C atom because it has a similar size, but the donor of choice, P, is quite a bit larger so that its incorporation rate during CVD growth is much smaller. The plasma-enhanced growth now being used improves the process, but the nonuniformities in the plasma can produce nonuniformities in the doping. This is especially true for the high-crystal quality substrates because they are small. This problem to some extent can be mitigated by the choice of the orientation of the substrate. Experiments have shown that the incorporation rate of P is low for the (001) orientation, higher for the (111) orientation, and more recently it has been shown to be even better for the (311) orientation.²²

Lateral diodes have been created in a clever way that have the desired substrate (001) orientation, while at the same time having the P doped n+ grown on the (111) plane. This was done by etching deep channels with (110) sidewalls of the substrate and selectively growing a right angle prism with the base parallel to the (111) plane.²³ No distinct defects are observed at the interface of the np junction diode by cross-sectional TEM, implying the good homoepitaxial growth of the n-type diamond. A very low leakage current less than 10–14 A in the reverse bias was obtained at room temperature, resulting in a high rectification ratio of 108. Although the rectification ratio decreases with increasing temperature, it is 106 even at 573 K. A breakdown voltage was determined to be more than 100 V.

Creating a structure like the ion-implanted p+n SiC diode is also not an option, because some graphite can be created by the implantation process and also during the high-temperature anneal required for activating the dopant. Surface graphite can also be formed if one attempts to create such a diode by in-diffusion of the dopant because high temperatures are required to create an acceptable diffusion rate given the strong bonds that diamond has.

7.3.3 Transistors

There are a number of different structures for diamond transistors, because diamond has so many unique properties. Most of them are FETs, but diamond can also be used to fabricate a BJT. As is the case for the GaN HEMT used for higher-power RF devices, all diamond FET structures are lateral devices with the source, drain, and gate in the same plane. However, for HPE applications, the structures of SiC and GaN devices are vertical in that the source and the gate are in the same plane, but the drain lies in a parallel plane beneath it. This enables a large portion of the voltage to drop across the channel region enabling these devices to block larger voltages even though they have smaller critical electric fields. Thus, the focus of

the diamond devices is RF electronics, where the primary competition is the GaN/AlGaN HEMT. The primary question is will it be possible to create a sufficiently large carrier concentration with the conducting carrier having a sufficiently high mobility so that the larger voltage that can be applied between the source and the drain can enable the diamond device to handle more power.

7.3.3.1 MESFETS

For the traditional metal–semiconductor field-effect transistor (MESFET), a FET with a metal gate, the current density is determined by the concentration and mobility of the carriers, as well as the thickness of the channel. In one example with a Pt gate,²⁴ the acceptor concentration (N_A-N_D) was estimated to be $4.7 \times 10^{15}/\text{cm}^3$, considering the depletion of the channel due to donors in the semi-insulating substrate, and the channel thickness was 3 μm . The maximum current density, I_{DS} , was only 0.06 mA/cm^2 . The small current density is attributed to most of the potential acceptors not being ionized. That this was the case is supported by the observation that the current density was 20 times larger when the transistor was heated to 300 °C.

This MESFET is also a normally on device, and the threshold voltage, V_{TH} is 27 V, which is quite large. It could be reduced by decreasing the thickness of the channel, but this would decrease the current density even more; one solution could be stringing a number of narrow-channel MESFETS in parallel. The breakdown voltage for this device with a 20- μm source to gate length was highly dependent on the variable gate-drain length and reached 1.5 kV at a gate-drain length of 30 μm ; the breakdown field for this device was 2.15 MV/cm , which is a good number, but the 50 μm of surface real estate is not.

7.3.3.2 JFETS

Normally off, junction-gate field-effect transistors (JFETs)²⁵ can be fabricated by modifying the n+p lateral diode described previously²³ by making the p-type region, doped to approximately $3 \times 10^{16} \text{ cm}^{-3}$, into the channel and the selectively grown n+ layer, doped to $8 \times 10^{19} \text{ cm}^{-3}$, grown in the [111] direction, into the gate. The combined depletion widths of these two n+ p junctions at zero bias is greater than the thickness of the channel, which is approximately 0.3 μm . The turn-on voltage is –1.2 V. However, because the acceptor depth is deep and the channel width is small, the saturation current density at room temperature is only 25 mA/cm^2 . Again, to consider this type of device for power applications, a large number of them would have to be connected in parallel.

The heavily B-doped layer can also be grown in a layered structure where a very thin layer—dope less than 2 nm—with sharp, well-defined boundaries doped to

greater than 1020 cm^{-3} that lies between two layers that are doped with B to approximately 1016 cm^{-3} .^{26,27} This structure mitigates B's high ionization energy by producing an acceptor subband, where approximately 100% of the B is ionized. Predictions have been made that RF FETs made with this structure would have a current capacity of 2.5 A/mm and RF power generation from 34 to 75 W/mm, depending on the gate structure and the desired frequency of operation. These remarkable properties are the result of the hole wave function being larger than the thickness of the delta layer, which allows a portion of the wave function to exist in the undoped layers where the hole mobility can be significantly higher than for a uniformly doped material.²⁷ There were numerous reports on devices fabricated with this delta-doped structure that were disappointing. It was suggested that the poor results are caused by nonuniform boron doping in the delta layer due to the boron clusters that were observed in high-resolution transmission electron microscopy (HRTEM) micrographs. Eventually, structures with resistances less than $10 \text{ k}\Omega/\text{sq}$ with mobilities from 16 to $120 \text{ cm}^2/\text{V}\cdot\text{s}$ were fabricated.²⁷

7.3.3.3 MISFETS

Rather than trying to use carriers created by deep acceptors or donors, one can utilize carriers created at interfaces, such as is done for MISFETs and HEMTs. However, traditional diamond MISFETs do not now appear to be a good candidate for HPE or higher-power RF devices. As noted previously, they cannot compete with very-high-power SiC devices because they cannot have a vertical device structure. Also, few dielectrics have the proper band structure to match the large E_G of diamond, and for one of the favorites, Al_2O_3 , the current status is that it has a large concentration of traps that leads to a low channel mobility and devices made with it often have low breakdown voltages.¹⁶

Rather than being used to help create the interface carriers, these dielectrics can be used in concert with H adsorbed on the (001) or (111) face of a B-doped diamond substrate to create a 2DHG.^{26,28} Two H atoms are bonded to a C atom on the (001) surface with the bonds being approximately parallel to the $[111]$ or (111) directions, while one H atom is bonded to a C atom on the (111) surface with the bond being parallel to the $[111]$ direction. The bonds are quite strong as indicated by the fact that the H does not begin to evaporate until $T > 900^\circ\text{C}$, and the 2DEG they create has a carrier concentration, n_c , of greater than 10^{13} cm^{-2} , which does not change much with the temperature.²⁶ The magnitude of n_c is a good number, but problems with its stability over time still have to be solved.²⁸ The hole mobility, the other important parameter for high power, as well as for high frequency should be improved by a factor of five for diamond devices to be competitive for HPHT applications,²⁷ and recent results suggest this has been achieved.²⁶

NO_2 reacts with H to form NO_3^- that creates a hole in the valence band, and a metal oxide about 30 nm thick is deposited on top to produce a more stable structure. Al_2O_3 , tungsten oxide (WO_3), molybdenum oxide (MoO_3), and V_2O_5 have all been used, but to date, Al_2O_3 deposited by ALD has produced the best results. However, the results have been difficult to reproduce, and some have suggested that Al_2O_3 can contain electron traps below diamond's valence band and that they could be responsible for the enhanced conduction.²⁶ But that being said, hydrogenated diamond devices coated with ALD Al_2O_3 have demonstrated a wide operational temperature range, -263 K to $400\text{ }^\circ\text{C}$, with an operating voltage greater than 1 kV, unity-current-gain frequency, f_T , of 70 GHz, and maximum frequency of oscillation, f_{max} , of 120 GHz.²⁵

7.3.4 Heterostructures

7.3.4.1 Diamond/c-BN HEMTs

With the spectacular success of GaAs/AlGaAs and GaN/AlGaN HEMTs, there has been talk about emulating it with creating diamond/c-BN HEMTs. The obvious attraction is that boron nitride (BN) has a large ξ_c , $(17.5\text{ V/cm})^{29}$ made possible by its large E_G (6.36 eV) and a large thermal conductivity ($2145\text{ W/cm}\cdot\text{K}$).²⁹ While all of the atoms in each of the structures have an sp^3 bonding structure, the diamond/c-BN HEMT structure is uniquely different in a number of ways:

- 1) The atoms come from different columns in the periodic table, and in the C/BN case, the atoms in one layer act as dopants in the other. This has been a problem for a number of applications that have attempted to use Si/GaAs structures.
- 2) The top layer, BN, is not a ternary so there is one fixed mismatch strain of 1.38% with BN having the larger lattice parameter. While the mismatch between GaN and AlN is 2.51%, the mismatch between 30% Al AlGaN is a little more than half of what it is between BN and C. Also 30% Al is considered to be the maximum amount of Al the AlGaN can contain without cracking, and its lattice mismatch is 0.75%. However, the AlGaN is in tension and therefore more prone to cracking, whereas the BN is in compression.
- 3) C does not have a polarization charge on any face and is not a piezoelectric material because it is a unitary material. BN does not have a polarization on any face because it is cubic, but it is piezoelectric because it is a binary material; the piezoelectric effect is maximized for growth on a $\{111\}$ plane. The growth of BN is initiated with the formation of C–B bonds, which gives

the BN film a (111) orientation,³⁰ and this orientation will generate a positive charge at the C–BN interface because the BN is in compression. This would encourage the formation of a 2DEG.

- 4) Traditionally, films with the cubic structure can be grown more smoothly with fewer structural defects when they are grown on the (001), and the most challenging surface to grow on is the (111) surface.
- 5) Like diamond, c-BN is not the most stable phase at atmospheric pressure. As a result plasmas will most likely have to be used for growth at lower temperatures to achieve growth of the cubic phase. Traditionally, films grown using a plasma have rougher surfaces and poorer structural quality. However, c-BN films have been grown on (111) diamond with smooth surfaces at 920 °C by ion-beam-assisted MBE, but they do contain stacking faults.³⁰

7.3.4.2 AlGaAs/GaAs/diamond HBTs

The lack of effective n-type dopants in diamond has limited the material to only unipolar p-type device applications. Heterostructure bipolar devices that use better n-type semiconductors together with p-type diamond is an approach to get high-performance devices such as p–n–p AlGaAs/GaAs/diamond HBTs fabricated using a grafting technique. GaAs and diamond have lattice and thermal mismatches that make epitaxial growth of high structural quality of these heterostructures virtually impossible. Direct material bonding of separate sections of these heterostructures results in a large density of defect states at the interface. An ultrathin oxide (UO)-interfaced semiconductor grafting approach is used instead of direct material bonding to try to minimize these structural defects. The UO is supposed to reduce the interface states and trap-assisted tunneling across the interface. Consequently, the Fermi-level pinning at the interface that occurs in direct material bonding could be minimized. The UO also serves as a thermal expansion buffering layer and material inter-diffusion barrier.

In this specific process,³¹ a GaAs/AlGaAs/GaAs (p+ contact / p emitter/ n+ base) layered membrane section is grown by MOCVD on an Al_{0.95}Ga_{0.05}As sacrificial layer grown on a GaAs substrate. The membrane is fabricated by first creating a 50- × 50-μm mesh of 9- × 9-μm square holes using an reactive-ion etch that penetrates to the Al_{0.95}Ga_{0.05}As sacrificial layer. The membrane is created by selectively etching the Al_{0.95}Ga_{0.05}As layer away using a deionized water and HF acid solution and floating the GaAs/AlGaAs/GaAs section off. The other section was composed of a high-quality (001) diamond substrate with the p+ subcollector grown on it and the p collector layer grown on top of it.

After completion of CMP process, the diamond structure was treated in boiling acid to achieve a partial oxygen termination condition. Following an RCA cleaning procedure, a five-cycle Al_2O_3 layer was deposited on the p-diamond surface using an ALD deposition system. The released E-B membrane was picked up from the GaAs substrate by a polydimethylsiloxane stamp and transferred to the Al_2O_3 -coated diamond substrate. The transfer process was performed in a nitrogen environment. The sample was annealed by RTP at 350 °C for 5 min under N_2 ambient to form the chemical bonding at the interface completing the GaAs/diamond grafting process.

While the initial results are promising, much more characterization and testing has to be done. The same structure could be constructed using other UWBG materials such as the one where N has replaced As in the HBT previously described.

7.3.5 Devices in High-Temperature Environments

Of all the UWBG semiconductors, diamond would benefit the most if the operating temperatures were greater than 500 °C; in fact, it would dominate the electronic device market because the vast majority of acceptors would be thermally ionized and most of the donors would be also. The more challenging problems would be how to protect the properties of the metal junctions from changing with time. Schottky diodes and MESFETs are discussed because they are the devices where there are much data at both room and higher temperatures.

The forward current density measured at a 2-V forward bias of a set of copper (Cu) Schottky diodes¹⁶ increases significantly with temperature from 3×10^{-2} at room temperature to 5×10^1 A/cm² at 600 °C. The increase per 100°C change in temperature is significant until approximately 500 °C, whereas the increase at 600 °C is small, suggesting that most of the acceptors are ionized at approximately 500 °C. The I-V characteristics of the diodes were almost unchanged after annealing them at 400 °C for 30 h. However, there was a small drop in V_{BR} from 952 to 713 V. These diodes showed clear rectification up to 700 °C, indicating they could operate temporarily at this temperature, but they did have problems with long time stability above approximately 500 °C, some of it due to the formation of graphite under the Schottky metal. The $I_{\text{F}}(4 \text{ V})/I_{\text{R}}(-4 \text{ V})$ ratio at room temperature, 3×10^4 , the similarity of the same ratio at 500 °C, 10^4 , and its precipitous drop as the temperature increases further to some extent mimics these results.

Increasing the temperatures of MESFETs has the same effect of beneficially increasing the number of carriers. In a specific example with a MESFET with a Pt gate that exhibited clear saturation and pinch-off characteristics, the drain current of the device was 20 times greater when it was operating at 300 °C than it was at

room temperature due to the activation of acceptors. The maximum I_{DS} and transconductance (gm) were increased from 0.06 mA/mm and 9.7 $\mu\text{S/mm}$ to 1.23 mA/mm and 61 $\mu\text{S/mm}$, respectively, by increasing the temperature.²⁴ Further, diamond MISFETs using Al_2O_3 gate insulators over H-terminated diamond channels performed nearly the same at 400 °C as at room temperature, with maximum current densities at 400 °C of approximately 32 mA/mm and gm values as high as 10 mS/mm.³²

7.4 References

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List of Symbols, Abbreviations, and Acronyms

2-D	two-dimensional
2DEG	two-dimensional electron gas
3-D	three-dimensional
AC	alternating current
AFOSR	Air Force Office of Scientific Research
ARFL	Air Force Research Laboratory
Al	aluminum
Al ₂ O ₃	aluminum oxide
ALD	atomic layer deposition
AlGaAs	aluminum gallium arsenide
AlGaO ₃	aluminum gallium oxide
AlGaN	aluminum gallium nitride
AlN	aluminum nitride
ARL	Army Research Laboratory
APD	avalanche photodiode
Ar	argon
ARPA-E	Advanced Research Projects Agency–Energy
AS	admittance spectroscopy
ASU	Arizona State University
Au	gold
BCl ₃	boron trichloride
BeO	barium oxide
BFOM	Baliga figure of merit
Bi ₄ Ti ₃ O ₁₂	bismuth titanate
BJTs	bipolar junction transistors

BN	boron nitride
BOPP	biaxially oriented propylene
C	carbon
CAD	computer-aided design
CaF ₂	calcium fluoride
CAVET	current aperture vertical electron transistor
c-BN	cubic boron nitride
CMOS	complementary metal–oxide–semiconductor
CMP	chemical mechanical polish
CMR	contour-mode resonator
COVID-19	SARS-CoV-2
CPU	central processing unit
CTE	coefficient of thermal expansion
CVD	chemical vapor deposition
Cu	copper
CW	continuous wave
DARPA	Defense Advanced Research Projects Agency
DC	direct current
DCE	dichloroethylene, C ₂ H ₂ Cl ₂
DCR	dark count rate
DCS	dihlorosilane, SiH ₂ Cl ₂
DETF	double-ended tuning fork
DEVCOM	US Army Combat Capabilities Development Command
DF	dissipation factor
DLOS	deep-level optical spectroscopy
DLTS	deep-level transient spectroscopy
DMOSFET	double-implanted MOSFET

DOD	Department of Defense
DOE	Department of Energy
DSC	dichlorosilane, SiH_2Cl_2
EFG	edge-defined film-fed growth
EMI	electromagnetic interference
ERI	Electronics Resurgence Initiative
EQE	external quantum efficiency
ESL	equivalent series inductance
ES	energy storage
ESR	equivalent series resistance
Fe	iron
FET	field-effect transistor
FIU	Florida International University
FOM	figure of merit
FWHM	full width at half maximum
Ga	gallium
Ga_2O_3	gallium(III) oxide
GaAs	gallium arsenide
GaN	gallium nitride
GaPO_4	gallium orthophosphate
Ge	germanium
H	hydrogen
H_3PO_4	phosphoric acid
h-BN	hexagonal boron nitride
HBT	heterojunction bipolar transistor
HCAFOM	chip area figure of merit
HEMT	high-electron-mobility transistor

HPE	high-power electronic
HPHT	high power high temperature
HRTEM	high-resolution transmission electron microscopy
HVAC	heating, ventilation, and air conditioning
HVPE	hydride vapor-phase epitaxy
IC	integrated circuit
ICP	inductively coupled plasma
IDT	interdigitated transducer
IGBT	insulated-gate bipolar transistor
In	indium
InP	indium phosphate
IPES	integrated power and energy system
IR	infrared
IT	information technology
I-V	current-voltage
JBS	junction barrier Schottky
JFET	junction-gate field-effect transistor
LED	light-emitting diode
LGS	langasite, $\text{La}_3\text{Ga}_3\text{SiO}_{14}$
LiNbO_3	lithium niobate
LLNL	Lawrence Livermore National Laboratory
LPCVD	low-pressure chemical vapor deposition
LRU	least-replaceable unit
LSM	lanthanum strontium magnetite, $\text{La}_{0.65}\text{Sr}_{0.35}\text{MnO}_3$
MacEtch	metal-assisted chemical etching
MANC	metal/amorphous nanocomposite
MBE	molecular beam epitaxy

MEMS	microelectromechanical system
MESFET	metal–semiconductor field-effect transistor
Mg	magnesium
MgF ₂	magnesium fluoride
MISFET	metal–insulator–semiconductor FET
MIT LL	Massachusetts Institute of Technology Lincoln Laboratory
Mo	molybdenum
MoO ₃	molybdenum oxide
MOCVD	metal-organic chemical vapor deposition
MOCATAXY	metal-oxide catalyzed epitaxy
MODFET	modulation-doped field-effect transistor
MOSFET	metal–oxide–semiconductor field-effect transistor
MSM	metal–semiconductor–metal
MSU	Michigan State University
MVAC	medium voltage alternating current
MVDC	medium voltage direct current
N	nitrogen
NEA	negative electron affinity
NETL	National Energy Technology Laboratory
NREL	National Renewable Energy Laboratory
NRL	Naval Research Laboratory
O	oxygen
ONR	Office of Naval Research
OSU	Ohio State University
PAMBE	plasma-assisted molecular beam epitaxy
PARC	Palo Alto Research Center
PCA	principal component analysis

PD	partial discharge
PEBB	power electronics building block
PEN	polyethylene naphthalate
PSU	The Pennsylvania State University
PTEOS	tetraethylorthosilicate
PIC	photonic integrated circuit
PLD	pulsed laser deposition
PN	phosphorus and boron
PnC	phononic crystal
PMUT	piezoelectric micromachined ultrasonic transducer
poly	polycrystalline
Pt	platinum
PTFE	polytetrafluoroethylene
PZT	lead zirconium titanate, $\text{Pb}_x\text{Zr}_{1-x}\text{TiO}_3$
RF	radio frequency
Rh	rhodium
RTA	rapid thermal annealing
SAG	self-aligned gate
SAW	surface-acoustic-wave
ScAlN	scandium aluminum nitride
Si	silicon
SiC	silicon carbide
SiO ₂	silicon dioxide
Sn	tin
SNL	Sandia National Laboratories
SNPD	Schottky np diode
SPDE	single photon detection efficiency

Sr	strontium
SSTR	steady-state thermo-reflectance
STEM	scanning transmission electron microscopy
SWaP	low-size, weight, and power
TCE	thermal coefficients of expansion
Ti	titanium
TiN	titanium nitride
TMO	transition-metal oxide
TOC	total organic carbon
TWT	traveling wave tube
UCSB	University of California, Santa Barbara
UO	ultrathin oxide
UWBG	ultra-wide bandgap
UV	ultraviolet
VCA	vertex component analysis
VCSEL	vertical cavity surface emitting laser
Virginia Tech	Virginia Polytechnic Institute and State University
V ₂ O ₅	vanadium oxide
W	tungsten
WO ₃	tungsten oxide
WBG	wide bandgap
WPE	wall plug efficiency
XRD	X-ray diffraction
Yb	ytterbium
ZnO	zinc oxide
α -Ga ₂ O ₃	alpha-phase Ga ₂ O ₃
β -Ga ₂ O ₃	beta-phase Ga ₂ O ₃

γ -Ga ₂ O ₃	gamma-phase Ga ₂ O ₃
ϵ -Ga ₂ O ₃	epsilon-phase Ga ₂ O ₃

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