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Ultrawide-Bandgap Semiconductors: Introduction and Key Parameters (Talk #1 of 5 for Special Session on UWBG Materials)

Mark A. Hollis,[1] Paul W. Juodawlkis,[1] and Robert J. Kaplar[2]
[1]MIT Lincoln Laboratory, 244 Wood Street, Lexington, MA 02420-9108
[2]Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185

Abstract: *The potential benefits of ultrawide-bandgap semiconductors for broad classes of applications was assessed in a recent workshop and summer study involving experts from academia, industry, and government. This talk will present an overview of these materials, including summary tables of key parameters and figures of merit, and will introduce the following 4 talks in this session.*

Introduction

The modern semiconductor-device era was inaugurated in 1947 with the demonstration of the first point-contact transistor in Ge at Bell Laboratories. This event launched a progression of research and development generations through various materials as shown below.

Generation 1. Ge, Si, and SiGe (1947 – 1996)

- Demonstration of first Ge transistor – 1947 (1956 Nobel Prize in Physics)
- Si bipolar transistors commercially available – late 1950's
- Integrated circuit invented – 1958 (2000 Nobel Prize in Physics)
- Si CMOS commercially available – late 1960's
- SiGe HBTs commercially available – 1992

Generation 2. III-V's: GaAs, InP, alloys (1950 – 1995)

- Concept of heterostructures – 1957 (2000 Nobel Prize in Physics)
- LED and solid-state laser invented – early 1960's
- GaAs RF MESFETs – late 1960's
- AlGaAs/GaAs 2-D electron gas – 1978
- GaAs MMICs and digital circuits – early 1980's
- GaAs pHEMTs and HBTs – 1983
- All-GaAs computer – 1989
- DARPA MIMIC Program – 1989 to 1995
    - Insertions into Longbow and Hellfire missiles – 1990
    - Rich legacy continues today

Generation 3. SiC, GaN, InGaN (1967 – 2016+)

- First epitaxial growth of GaN – 1968
- ONR internal study on wide-bandgap materials – 1971 to 1974 [1]
- ONR-funded university research in SiC, GaN – late 1970's
- ONR funding expands in Reagan SDI era
- SiC bulk growth and GaN epitaxial growth – late 1980's
- Japanese research in GaN/InGaN for blue LEDs (2014 Nobel Prize in Physics [2])
- SiC power devices commercially available – mid-1990's
- First AlGaN/GaN HEMT – 1993
- DOE investments for efficient lighting and power – 1990's forward
- ONR and DARPA heavily invest in GaN for RF power and MMICs – 2000 forward
- Low-cost, efficient LED lighting commercially available – 2010
- GaN insertions into military systems – 2007 forward

The first significant U.S. investments in wide-bandgap semiconductors were in Generation 3, which has culminated in substantial ONR and DARPA programs to reap the benefits of GaN for military systems, as well as DOE programs for energy. The development of these GaN devices over the last two decades has been a major success story for the U.S. government/industry partnership with GaN devices now being transitioned into present and next-generation military systems.

Generation 4: The Next Wave. As with ONR in the early 1970's, there has been a growing recognition that there are materials with even wider bandgaps that have greater untapped potential, and that now may be the time to start the next cycle of materials development. So-called ultrawide-bandgap (UWBG) materials such as AlGaN, AlN, Ga_2O_3, cubic BN (c-BN), and diamond having bandgaps above that of GaN (> 3.4 eV) offer significantly greater capability for power switching and RF power, and some offer greater (or newly available) capability for deep-UV optoelectronics and quantum information systems. In addition, many offer better promise for operation in extreme environments where radiation damage and/or high temperatures obviate other materials from consideration.

Toward this goal, a workshop was held in Arlington, VA, on 24-25 April 2016 in which experts from academia, government, and industry were convened to discuss these ultra-wide-bandgap (UWBG) materials, the physics, the possible devices, and their applications in order to identify research opportunities and challenges. Subsequent to the workshop a number of the experts worked throughout the summer to research outstanding questions on critical issues and compile a report and summary tables of materials parameters and figures of merit (FOMs) for the relevant applications. This study constitutes the most comprehensive compilation and updating of such information on these materials known. In a number of cases the study found that the values of some materials parameters that are in common usage are out of date and based on early measurements of disordered material grown decades ago. The study also examined important questions such as how critical breakdown field varies with bandgap (and alloy composition for AlGaN), and how reported critical-field values for different diode designs in different materials may be compared on a level playing field. The detailed findings and parameters of the study are too extensive to enumerate here, but can be found in an extensive review article that will soon be published [3].

Fortunately, in this present paper we can highlight some of the more important findings in areas such as power switching, RF power, and quantum information sciences. Because many of the figures of merit for device performance scale with increasing bandgap or other parameters in a non-linear manner, such UWBG materials have the potential for performance far superior to that of conventional WBG materials. For example, in the case of a low-frequency unipolar vertical power switch, the Baliga figure of merit (BFOM, [4]) is defined as V_{BR}^2/R_{ON-SP}, where V_{BR} is the breakdown voltage (the maximum voltage the switch can block when it is off), and R_{ON-SP} is the specific on-resistance (the inverse of the conductance per unit area when the switch is on). The higher the BFOM, the higher the voltage the device can block when off and/or the higher its conductivity per unit area when on. The BFOM can be expressed in terms of the critical breakdown field E_C as BFOM = $\frac{1}{4}\varepsilon\mu E_C^3$, where ε is the electric permittivity and μ is the majority carrier mobility. The critical electric field, in turn, scales approximately as the square of the semiconductor bandgap, so the BFOM scales approximately as the *sixth power* of the semiconductor bandgap. As an illustration, an increase in bandgap by a factor of 6.0 eV/3.4 eV ≈ 1.8 in going from GaN to AlN translates to an increase in the BFOM of $(1.8)^6 \sim 34$X. Lines of constant BFOM are drawn in Fig. 1 on a specific-on-resistance versus breakdown-voltage plot and correspond to various conventional, WBG, and UWBG semiconductors. Note that the lines corresponding to the UWBG semiconductors trend towards the higher performance lower-right region of the plot.

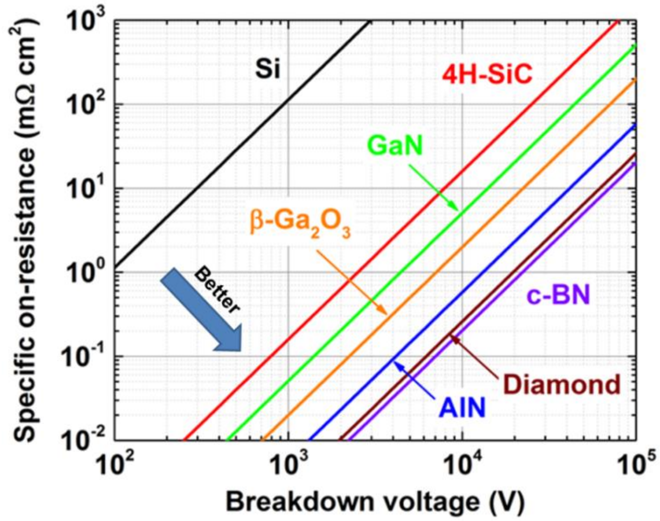

Figure 1. Lines of constant Baliga figure of merit (BFOM) for conventional, WBG, and UWBG semiconductors. This is the figure of merit relevant for low-frequency unipolar vertical power switches. Clearly the UWBG materials are expected to exhibit superior performance.

Similarly, for RF power the Johnson figure of merit (JFOM) is the one in most common use and in its simplest form is expressed as JFOM = $v_{sat} \cdot E_C$, where v_{sat} is the saturated carrier velocity in the material [5]. The higher the JFOM, the greater the promise of a given material for generating higher RF power at high frequencies. In addition to the electrical performance described by the JFOM, thermal conductivity is also extremely important for RF power devices and especially will be so for those made of UWBG materials as the projected power capability (power density and power output) is expected to be substantially higher which also increases the waste heat load. Table 1 provides a comparison of these relevant parameters for RF power devices for the candidate UWBG materials. The figures of merit and materials parameters in both Fig. 1 and Table 1 are derived from the refreshed parameters found in the summer study, and came from either the best original source references or the latest physical derivations [3].

Table 1. Johnson Figure of Merit and Thermal Conductivity for RF Power Devices

Material	v_{sat} (10^7 cm/s)	E_C at N_D = 10^{16} cm^{-3} (MV/cm)	Thermal conductivity (W/m-K)	JFOM = $v_{sat} \cdot E_C$ (10^{12} MV/s)
Si	1.0	0.3	145	3
GaN	1.4	4.4	140	62
AlN	1.3	13.7	319	180
β-Ga_2O_3	1.1	9.1	27	100
c-BN	unknown	15.6	940 / 2145 Natural / Isotop. pure	--
Diamond	2.3	11.5	2290 / 3450 Natural / Isotop. pure	260

Thirdly, quantum information science (QIS) is a rapidly evolving field with the potential to impact multiple areas, including: position determination, navigation and timing; tunnel detection; code breaking; secure communications; high-speed computation; and magnetic anomaly detection [3]. UWBG semiconductors have potential roles in QIS as 1) transparent hosts for dopants and defects with electronic/spin states suitable for quantum information processing, and 2) photonic platforms for quantum processors based either on trapped-ion quantum bits (qubits), or linear optical quantum computation (LOQC) in which photons serve as the qubits. In trapped-ion quantum processors, the quantum information is contained in the states of the ions and these states are typically initiated and read out by exciting each ion with lasers at a number of different wavelengths. In LOQC systems, the quantum information is represented by the states of single photons and these states are manipulated by linear optical elements (e.g., beam splitters, phase shifters, and mirrors).

In the host role, UWBG semiconductors host defect-related electronic/spin states that are sufficiently decoupled from the lattice to be long-lived. Prototypical systems are the nitrogen-vacancy (N-V) or silicon-vacancy (Si-V) centers in diamond, which display long spin-relaxation times and can be interrogated optically. These systems were among the first to have been considered for quantum information and continue to be an active area of research, including the possibility of incorporating these centers into diamond devices where a gate bias controls the charge state of the center and affects its quantum characteristics.

In the photonic-platform role, UWBG semiconductors may be used for the generation, manipulation, and interrogation of quantum states. Indeed, all of the necessary photonic building blocks could potentially be based on UWBG semiconductors, and in particular on AlN/AlGaN: narrow-linewidth lasers, high single-photon-detection-efficiency avalanche photodiodes, waveguides for photonic integrated circuits, and nonlinear optical media for wavelength conversion to spectral regions more suitable for low-loss transmission of photon-based quantum information (i.e., the 1300- to 1600-nm telecom band).

This study concluded with a recommendation that Development Generation 4 be initiated in UWBG materials and relevant devices to ensure continued U.S. electronic, optoelectronic, and quantum-information superiority into the middle and latter half of the 21st Century. This conference presentation gives an overview of the study objectives and introduces the following 4 talks of this session which comprise Materials, Physics, Devices and Applications, and Research Challenges and Opportunities. In addition, summary tables of updated materials parameters and FOMs will be presented and will be used to highlight important findings. Finally, this talk will discuss widely held myths about UWBG materials as well as truths that are not widely known.

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