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Masataka Higashiwaki and Gregg H. Jessen

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Guest Editorial: The dawn of gallium oxide microelectronics

Masataka Higashiwaki[1,a)] and Gregg H. Jessen[2,b)]
[1]National Institute of Information and Communications Technology, Koganei, Tokyo 184–8795, Japan
[2]Air Force Research Laboratory, Wright-Patterson Air Force Base, Dayton, Ohio 45433, USA

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Among semiconductors, Si is the foundational technology against which all others are compared. The bandgap is large enough to allow for the conductivity of the material to be controlled from semi-insulating to fully conductive but small enough such that both *n*-type and *p*-type impurities can be fully ionized. The level of integration achievable by Si is unmatched by any other semiconductor technology, and its application space is vast including digital logic, memory, RF, power switching, and even optoelectronics. Yet, as we approach the atomic limit of scaling for Si to reach the pinnacle of its performance, we see the fundamental limitations of its performance at the device level. There still remain applications and functions that are out of reach for this material. For power switching applications, the operating voltage is limited by the electric field strength at which breakdown occurs (E_{br}) and minimum achievable background doping in epitaxial drift layers while minimizing total energy loss is limited by resistive power dissipation during on-state current conduction and capacitive loss during dynamic switching. For RF applications, the maximum power achievable at higher frequency is limited by the power frequency product. These are fundamental performance limitations directly related to the E_{br} of the material which is strongly correlated with the bandgap.

In the quest for performance, various compound semiconductors with a larger bandgap have been developed for applications which are complementary to Si technology when Si cannot provide sufficient power density to achieve required metrics. Consequently, GaAs, SiC, and GaN have shown tremendous advances for both RF power amplification and power switching. However, materials with a bandgap greater than 3.3–3.4 eV, which is the value for SiC and GaN, come with many technical challenges. As the bandgap energy increases, the ionization efficiency of intentional dopants decreases, as does the likelihood of having both *n*-type and *p*-type conductivities. In addition, there exist no large-area, native substrates with a bandgap larger than 3.4 eV which can achieve a large range of conductivities. It is here that we turn to the transparent conductive oxide family of semiconductors, in which gallium oxide (Ga_2O_3) is unique and attractive.

Ga_2O_3 is by no means a new material. The properties of bulk single crystals were first studied in the 1950–1960s[1,2] with more recent melt and epitaxial growth technologies developed into the 1990s. However, in the last five years, Ga_2O_3 has attracted great attention due to a combination of unique material properties and substrate availability. The majority of the efforts to date have been devoted to monoclinic β-Ga_2O_3 due to its thermal stability, resulting in it being the most readily available. There are four other metastable polymorphs labeled α, γ, δ, and ε. Recently, these other polytypes have received increased attention due to unique properties not found in the β-phase. Corundum α-Ga_2O_3 is the second most studied polytype behind the β-phase because of its ease of heteroepitaxial growth on sapphire substrates. γ- and δ-Ga_2O_3 have defective spinel and cubic bixbyite-like structures, respectively. Hexagonal ε-Ga_2O_3 is of interest due to internal polarization that could lead to the formation of high-density two-dimensional electron gas (2DEG) at the $(AlGa)_2O_3/Ga_2O_3$ interface similar to AlGaN/GaN-based heterostructures. These metastable-phase Ga_2O_3 films are mostly obtained by low-temperature heteroepitaxial growth on foreign substrates and are easily converted into the most stable β-phase during high-temperature thermal annealing. Therefore, in this editorial, we will focus on β-Ga_2O_3.

The main motivation for research and development (R&D) on β-Ga_2O_3 is inspired by its incredibly large bandgap, which is estimated to be around 4.5–4.9 eV.[2–5] Due to the complex band-structure of β-Ga_2O_3, a wide range of high E_{br} from 5 to 9 MV/cm can be estimated from the bandgap using methods outlined by Hudgins *et al.*[6] E_{br} is more than double the theoretical limits of SiC and GaN and translates to more than triple their power device performance predicted from the Baliga figure of merit, which is most commonly used to evaluate the suitability of a material for power switching devices.[7] Additionally, a wide range of electron densities from $\sim 1 \times 10^{15}\,\mathrm{cm}^{-3}$ to $>1 \times 10^{20}\,\mathrm{cm}^{-3}$ has been demonstrated by intentional donor doping in epitaxial materials. The ability to reduce DC conduction losses in devices by minimizing on-resistance (R_{on}) and maximizing breakdown voltage (V_{br}) lends to high-power and high-voltage applications and, when combined with advanced scaling techniques, high-speed switches for low/medium-power applications. According to the Johnson figure of merit,[8,9] which is another benchmark for high-frequency power devices, the power frequency product for Ga_2O_3 is comparable to that for GaN because even though the saturation electron velocity in Ga_2O_3 is lower than that in GaN, the extremely large E_{br} of Ga_2O_3, which is more than double that of GaN, can compensate for the shortcoming. These properties combined with the availability of high-quality, large-area native substrates offer a complete platform for various applications such as high-performance power switching, RF amplifiers, and harsh-environment signal processing.

[a)]Electronic mail: mhigashi@nict.go.jp
[b)]Electronic mail: gregg.jessen@us.af.mil

To date, Ga_2O_3 has achieved many key milestones for technology viability. The existence of high-quality Ga_2O_3 wafers manufactured from bulk single crystals that can be synthesized by several melt growth methods, such as float zone,[10–12] Czochralski,[13,14] vertical Bridgman,[15] and edge-defined film-fed growth (EFG),[12,16] is one of the most important material features. Ga_2O_3 wafers with diameters as large as 2 in. for (001), 4 in. for $(\bar{2}\,01)$, and 1 in. for (010) are presently available. The melt-grown bulk single crystals offer a significant advantage of Ga_2O_3 over SiC and GaN in terms of production cost because SiC and GaN bulk crystals require alternative synthesis techniques using higher pressure and higher temperature. From a physical perspective, high-quality Ga_2O_3 wafers also provide a unique opportunity to study epitaxial materials in which the lowest possible number of dislocations can be obtained.

Although polycrystalline Ga_2O_3 thin films have been used for decades as a transparent, charge dissipation layer for optical applications, epitaxial growth technology of single-crystal Ga_2O_3 thin films remains to be established. Several techniques such as molecular beam epitaxy (MBE),[17–23] pulsed laser deposition,[3,24,25] halide vapor phase epitaxy (HVPE),[26–28] metalorganic chemical vapor deposition,[29–32] mist chemical vapor deposition (mist-CVD),[33–36] and low pressure chemical vapor deposition[37] have been used for the epitaxial growth of Ga_2O_3-based materials on both native and non-native substrates. Each technique has some drawbacks and advantages. However, to date, MBE and HVPE have shown the best control over electron density.

With intentional shallow donors (Si, Ge, and Sn) and deep-level compensating acceptors (Mg and Fe), n-type conductivity is controllable over fifteen orders of magnitude, i.e., from highly conductive ($\sim 10^{-3}\,\Omega\,\text{cm}$) to semi-insulating ($\sim 10^{12}\,\Omega\,\text{cm}$). However, as is typical with other oxide semiconductors, it is unlikely that p-type doping can be achieved with effective hole conduction in Ga_2O_3. Shallow acceptors are not predicted for Ga_2O_3, and hole transport is further restricted by its valence band structure. It is known from theoretical calculations that the valence band maximum of Ga_2O_3 has very small dispersion, leading to an extremely large hole effective mass.[4,38,39] Furthermore, a unique phenomenon that holes are inherently self-trapped in the Ga_2O_3 bulk has also been predicted.[40] Therefore, it is expected that unipolar Ga_2O_3 device applications will dominate, while bipolar devices will be difficult to realize.

β-Ga_2O_3 has multiple phonon modes in the low-energy range due to its band structure.[41,42] The low-energy polar optical phonons result in a dominant scattering factor that limits room-temperature electron mobility to 200–250 $\text{cm}^2/\text{V s}$.[43] On the other hand, the saturation electron velocity is estimated to be around 2×10^7 cm/s from theoretical calculations,[44] which is suitable for high-frequency operation. Although the mobility of Ga_2O_3 is lower than those of traditional compound semiconductors, the cubic dependence of DC conduction loss on E_{br} allows superior switching performance. Furthermore, for RF applications, the large E_{br} can support extreme scaling of the Ga_2O_3 field-effect transistors (FETs), allowing the electron velocity to reach saturation at a reasonable operating voltage.

Poor thermal conductivity is expected to be an engineering challenge for high-power Ga_2O_3 devices.[45–47] Packaging solutions for cooling devices will necessarily be a combination of topside thermal shunts and backside heat extraction through a thinned wafer mounted to a heatsink. Wafer bonding processes are particularly advantageous for overcoming poor heat dissipation caused by the low thermal conductivity of Ga_2O_3. Alternatively, structures consisting of thin Ga_2O_3 drift layers transferred to a supporting substrate with high thermal and electrical conductivities may be favorable for high-voltage and high-power vertical device applications.

Two fundamental device components for power conversion systems, Schottky barrier diodes (SBDs) and FETs are intensively being developed. Initial Ga_2O_3 SBDs made use of native n-type Ga_2O_3 substrates to evaluate the basic device performance.[48–50] However, Ga_2O_3 SBDs lagged behind FETs in development progress in the early years due mainly to a lack of suitable epitaxial growth techniques for thick n-Ga_2O_3 drift layers. The advancement of epitaxial growth technologies made it possible to obtain high-quality drift layers with a reasonably low electron density and led to acceleration of the SBD development.[51–53] One of the state-of-the-art Ga_2O_3 SBDs with an HVPE-grown drift layer demonstrated promising characteristics such as a reasonably low specific R_{on}, a reverse V_{br} over 1 kV, and an ideality factor close to unity.[54] Given more sophisticated edge termination structures used in Si and SiC power diodes, Ga_2O_3 SBDs should be able to be operated at much higher voltages. Another unique fabrication approach of free-standing α-Ga_2O_3 SBDs was also reported.[55] The α-Ga_2O_3 SBDs were fabricated through a lift-off of an epitaxial layer grown by mist-CVD on a sapphire substrate. The removal of the sapphire substrate and direct bonding of the device active area to a heat sink is effective in promoting heat dissipation.

The first single-crystal Ga_2O_3 transistors by means of metal-semiconductor FETs (MESFETs) were demonstrated in 2011.[56] The MESFETs developed into depletion-mode (D-mode) metal-oxide-semiconductor FETs (MOSFETs) in 2013,[57] which are the basic lateral Ga_2O_3 FET structures for current work. To date, D-mode Ga_2O_3 MOSFETs have demonstrated a large on/off ratio exceeding ten orders of magnitude,[57,58] stable operation up to 300 °C,[57,58] mean and peak electric fields in the Ga_2O_3 channel exceeding 3.8 and 5.3 MV/cm, respectively,[59] and pulsed drain current density exceeding 450 mA/mm.[60] Note that the peak value reported for E_{br} is much larger than the theoretical limits of SiC and GaN. Advanced D-mode Ga_2O_3 MOSFETs with a gate-connected field plate have achieved off-state V_{br} as high as 755 V.[61] D-mode Ga_2O_3 substrate-gated, nanomembrane FETs with minimal self-heating effects demonstrated a record high drain current density of 1.5 A/mm,[62] which is comparable to typical values achieved in GaAs- and GaN-based FETs. Enhancement-mode (E-mode) FETs enabling normally off operation are strongly desired for power switching for fail-safe functionality. Early E-mode results were obtained with wrap-gate devices achieving $V_{br} > 600$ V,[63] followed by lower voltage demonstrations using nanomembrane FETs[62] and MOSFETs with an unintentionally doped channel layer.[64] Developments of vertical Ga_2O_3 FETs that are more suitable for high-voltage, high-power applications are starting to be reported.[65–67]

Device developments required for low series resistance and increased V_{br} in power switching FETs are mostly applicable to RF FETs. In addition, high-speed switching and high-frequency operation require short-gate device structures. The electron velocity in Ga_2O_3 is expected to saturate around 30 V/μm, which is almost equal to the E_{br} value of Si. Thus, highly scaled device topologies favoring high electric field profiles are required for high-performance operation of lateral RF FETs in Ga_2O_3. Highly scaled device structures with self-aligned electrodes fabricated by ion implantation are also considered to be viable and to be compatible with advanced scaling techniques used in industry. The first RF device characteristics of Ga_2O_3 MOSFETs with a gate length of 0.7 μm showed a maximum oscillation frequency of 13 GHz at a drain voltage of 40 V and a output power density >250 mW/mm at 800 MHz.[68]

Very recently, significant progress in the development of $(AlGa)_2O_3/Ga_2O_3$ modulation-doped FETs (MODFETs), which are analogous to AlGaAs/GaAs MODFETs, has been demonstrated.[69–71] Unlike GaN-based heterostructures, there is no internal polarization in the monoclinic β-Ga_2O_3 structure. Therefore, formation of a high-density 2DEG induced by polarization doping is not expected at the $(AlGa)_2O_3/Ga_2O_3$ interface. However, the MODFET structure does provide an advantage for channel charge control by applied gate voltage, which is especially important for highly scaled devices.

Ga_2O_3 is a unique material with many attractive properties. Studies of material physics, defect characterization, dielectric interfaces, and development of device technologies on this new semiconductor have just begun and remain open-ended. Practical power switching and RF device applications require more advanced device architectures and thus demand further improvements in all aspects of melt/epitaxial growth, doping, and device processing and deeper understanding of fundamental material properties to be included in new modeling capabilities that are accurate under high-electric field operating conditions. R&D in the next decade is certainly crucial for the road to industrialization of Ga_2O_3 electronic devices. We hope that you will find this reference useful and be inspired to join in the development of Ga_2O_3 microelectronics.

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