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COMMENTS AND OPINIONS

# Gallium oxide: promise to provide more efficient life

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**Jincheng Zhang** talks to **Yue Hao** about the importance of this emerging and promising field.

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***Despite being the long-time mainstream semiconductor for both logic and power devices, Silicon is now facing its dilemma and limitation of scalability and material potential. Especially for power devices, people are demanding escalating efficiency with higher blocking voltage while its power consumption and heat generation are less. Constrained by its narrow bandgap of 1.14 eV, Silicon only has a critical breakdown field ($E_c$) of 0.3 MV/cm, yielding a Baliga figure-of-merit (BFOM = $\varepsilon \times \mu \times E_c^3$) of unity when normalized to itself. It is hence required that the dominating factor $E_c$ should be as high as possible such that the BFOM will be hundreds or even thousands of times when compared to Silicon so as to minimize the conduction loss. Beta-Gallium Oxide ($\beta$-$Ga_2O_3$) with decent $\mu$ of 250 cm²/Vs, ultra-wide bandgap of 4.8 eV and high critical $E_c$ of 8 MV/cm, yielding a superior high BFOM of more than 3000. Therefore, system made with $\beta$-$Ga_2O_3$ can be thinner, lighter and capable of handling more power than the one with Silicon. In addition, low-cost and large size substrate through melt-grown method endows $\beta$-$Ga_2O_3$ more potentials as cost-effective power devices. After resolving the low thermal conductivity issue, unipolar devices made with ultra-wide bandgap $\beta$-$Ga_2O_3$ are promised to make power transition and our life more efficient.***

**What is *Beta Gallium Oxide*?** The emerging beta-phase (β-) $Ga_2O_3$ is a semiconductor and it is the most stable one among all five phases, namely α, β, γ, δ, and ε. Other polymorphs are metastable and will convert into β phase at an elevated temperature of 750–900 °C. It has a monoclinic crystal structure with lattice constant of $a$ = 12.2 Å, $b$ = 3.0 Å and $c$ = 5.8 Å and a particular angle of 104° is presented between the $a$ and $c$ axis. The unit cell possesses two crystallographically inequivalent Ga positions, one with tetrahedral geometry Ga and one with octahedral geometry Ga. The oxygen atoms are arranged in 'distorted cubic' array and they have three crystallographically different positions. Two oxygen atoms are coordinated trigonally and one is coordinated tetrahedrally. The different position of Ga and O atoms leads to an anisotropic optical, electrical and physical properties, for example its different thermal conductivity at (–201), (100), (010) and (100) planes. The bandgap is around 4.8 eV from both hybrid density functional theory (DFT) calculation and absorption and resolved photoemission measurement. The effective mass of electron and hole are extracted to be 0.3$m_o$ and 40$m_o$, respectively, where $m_o$ is the free electron mass. Due to the low electron effective mass, the intrinsic electron mobility is 250 cm²/Vs, which is much higher than other oxide semiconductors. Unlike other ultra-wide bandgap semiconductors AlN and diamond, the β-$Ga_2O_3$ can be easily doped with Si, Sn, Ge and Nb, so that the medium-doped β-$Ga_2O_3$ can be very conductive with low resistance at on-state and very insulating at off-state. Finally, the anisotropic thermal conductivity ranges from 10 to 25 W/mK depends on its surface orientation. To sum up, β-$Ga_2O_3$ is a thermal stable ultra-wide bandgap semiconductor with $E_g$ = 4.8 eV, decent intrinsic electron mobility of 250 cm²/Vs, and the capability of being controllable doped.

**Why β-$Ga_2O_3$ and What is the Application Field?** Due to its ultra-wide bandgap of 4.8 eV, β-$Ga_2O_3$ has a critical breakdown field $E_c$ of 8 MV/cm, which is more than 20 times of Si and 2–3 times of GaN and SiC. Combined with the 250 cm²/Vs intrinsic electron mobility, β-$Ga_2O_3$ has a Baliga FOM (BFOM = $\varepsilon \times \mu \times E_c^3$) of more than 3000, which is around 4 times of GaN, 10 times of SiC and 3000 times of Si. BFOM is a judgment factor of representing how ideal of this material can be applied as power device channel. With higher BFOM, the devices are able to deliver higher power with less consumption and heat generation. To simplify the understanding, higher BFOM tends to allow the power device to have a lower specific on-resistance ($R_{on,sp}$) at the same breakdown voltage (BV) or higher BV at the same $R_{on,sp}$. In other words, the wasted power and energy is less, leading to a higher efficiency. Moreover, according to the Johnson FOM (JFOM = $E_c^2 \times v_{sat}^2/4\pi^2$), which is another benchmarking factor for high-frequency power devices, the power frequency product for β-$Ga_2O_3$ is 2 and 10 times of GaN and SiC, because of its high saturation electron velocity ($v_{sat}$) of $2 \times 10^7$ cm/s. These properties combined with the availability of high-quality and large-size native substrates through melt-grown methodology offers a complete platform for various applications of β-$Ga_2O_3$ such as high performance power switching, RF amplifiers, and harsh environment signal processing, although the main application of β-$Ga_2O_3$ is for power switching.

**What is the Recent Progress?** To date, β-$Ga_2O_3$ has achieved many remarkable progresses on substrate, Schottky barrier diodes (SBDs) and field effect transistors (FETs), even this field is just explored for around 5 years. 4 inch low defect density and atomically flat substrate is available from edge defined film-fed growth (EFG)-grown method, which is advantageous over SiC and GaN in terms of production and cost since those latter 2 native substrates require alternative synthesis techniques using higher pressure and higher temperature. Averaged *E* of more than 5 MV/cm is demonstrated, which is around twice of the critical *E* of GaN and SiC. As for the Schottky Rectifiers, a high BV of 2.2 kV and 3 kV are achieved on vertical and lateral diodes at this premature stage. Record-high output current density of 1.5/1 A/mm of D/E-modes FETs are demonstrated and it is comparable to the GaN-based FETs, whose development duration is more than 20 years. Both vertical and lateral FETs have achieved kV-class BV on fin-shaped vertical and field-plated planar devices. Although the RF device is lagged behind the power device, β-$Ga_2O_3$ FETs with $f_T/f_{amx}$ of 5.1/17.1 GHz and negligible current collapse also pave the foundation of applying β-$Ga_2O_3$ FETs as power amplifiers. In conclusion, significant achievements have been obtained including large-diameter substrate growth, high critical *E* demonstration, high BV of both SBDs and FETs with high current density achievement and the preliminary study on the RF performance.

**Remained Challenge and Prospect?** Obviously, there are several challenges of implementing β-$Ga_2O_3$ in power electronics. The primary concern is its low thermal conductivity. Nanomembrane lift-off and wafer transfer techniques are two possible approaches after bonding the thin-layer to a high thermal conductivity diamond or AlN substrate. P-type conductivity seems to be a physically scarcely possible mission, however we can still use unipolar devices at present. Some other minor challenge includes, 1) larger diameter substrate to minimize the cost, 2) high-quality passivation and dielectric layer to reduce the interface trap states and improve the reliability and 3) advanced device architectures and effective edge termination techniques to let the averaged *E* to be close to its theoretical value 8 MV/cm so as to enhance the BV at the same dimension and make the $R_{on,sp}$–BV relationship more ideal. Next ten years will be a crucial period for the β-$Ga_2O_3$: move from experimental level to commercial available product. Further improvements in all aspects of epitaxial growth, material doping, device processing technologies and thermal management in addition to a comprehensive understanding of fundamental material science will accelerate the commercialization of β-$Ga_2O_3$ based transistors and diodes and as a return making our life more efficient.

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