β-Ga_2O_3 Crystal Growth and Device Processing

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Abstract

Development of β-Ga_2O_3 power devices has been accelerating over the past few years. In particular, 4-inch device-quality β-Ga_2O_3 epi wafers have become commercially available, and low-loss trench MOS-type SBDs, few-kV finFETs, and normally-off MOSFETs have been demonstrated. In this paper, we will explain recent progress in crystal growth techniques for β-Ga_2O_3 and power devices based on this material.

INTRODUCTION

Ga_2O_3 exists in five phases. The most stable is the β-phase. Figure 1 shows the crystal structure of this phase, which is monoclinic. The material properties of β-Ga_2O_3 and major semiconductors are summarized in Table 1 [1]. β-Ga_2O_3 has a huge bandgap of 4.5-4.9 eV. The critical electric field strength is expected to be 6-8 MV/cm. Its carrier concentration can be controlled in the range of 10^{15}-10^{20} /cm^3 by Si or Sn doping [2, 3]. The electron mobility is around 200-300 cm^2/Vs. From these material properties, Baliga's figure of merit for β-Ga_2O_3 reaches a huge value, 3,444. This means that ultra-low-loss power devices can be fabricated by using β-Ga_2O_3. Another important feature of β-Ga_2O_3 is that bulk crystals can be grown using the melt growth method at low cost. Accordingly, β-Ga_2O_3 is an attractive material for next-generation power devices.

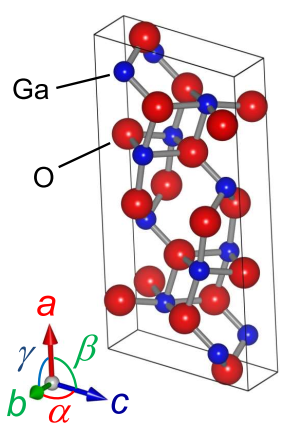


Fig. 1. Crystal structure of β-Ga_2O_3.

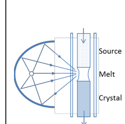
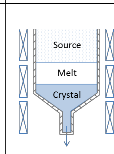
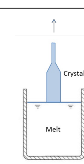
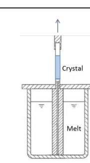
Table 1. Material properties

	Si	4H-SiC	GaN	β-Ga_2O_3
Bandgap: E_g (eV)	1.1	3.3	3.4	**4.5-4.9**
Electric field strength: E_c (MV/cm)	0.3	2.5	3.3	**8.0(est.)**
Mobility: μ_e (cm^2/Vs)	1,400	1,000	1,200	**300(est.)**
Dielectric constant: ε_s	11.8	9.7	9	**10**
Baliga's FOM: $\varepsilon\mu E_c{}^3$	1	340	870	**3,444**

β-Ga_2O_3 BULK CRYSTAL GROWTH

The techniques for growing large β-Ga_2O_3 bulk crystals include standard methods such as Czochralski (CZ), floating zone (FZ), edge-defined film-fed growth (EFG), and vertical Bridgman (VB) method. Table 2 compares the bulk growth methods reported for β-Ga_2O_3. In particular, FZ method does not use crucible, and it can grow high-purity crystals. The development of the VB method has progressed rapidly in the last few years, and 2-3-inch wafers have already been demonstrated. CZ method is widely used for many materials to make large boules. However, in the case of Ga_2O_3, there is an issue regarding n-type doping, wherein the shape of n-doped crystals easily becomes like a coil. The development of the EFG method is the most advanced, and 100-mm wafers are commercially available (see fig. 2). The dislocation density of 100-mm wafers is low enough, about 10^3-10^4 /cm^2. 150-mm wafers were demonstrated a few years ago [4].

Table 2. Comparison of β-Ga_2O_3 bulk growth methods.

Method	FZ	VB	CZ	**EFG**
				
Bulk size reported	1 inch	2 inch	2 inch	**6 inch**
n-type doping	Possible	Possible	Difficult	**Possible**
Growth rate (mm/h)	5	0.5	2	**15**
Strong point	High purity	High quality	Large boule	**Large n-type**

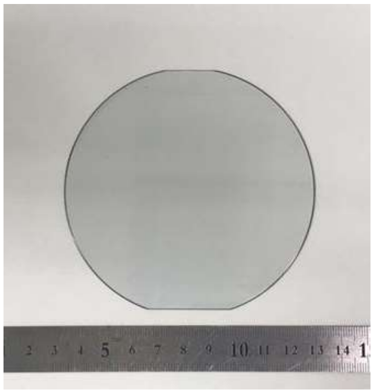


Fig. 2. 4-inch β-Ga_2O_3 single crystal substrate.

β-Ga_2O_3 EPITAXIAL GROWTH

High-voltage β-Ga_2O_3 power devices require high-quality and thick epitaxial films with a low donor concentration. The development of epitaxial growth techniques is underway using molecular beam epitaxy, halide vapor phase epitaxy (HVPE), metal organic chemical vapor deposition (CVD), mist CVD, etc. HVPE is the most suitable method for power-device applications because a high-purity and thick layer can be grown [5]. Figure 3 shows a schematic illustration of a β-Ga_2O_3 HVPE system, which was developed by Novel Crystal Technology, Inc. (NCT), the Tokyo University of Agriculture and Technology, and National Institute of Information and Communication Technology. The reactor is divided into two zones. In the source zone, GaCl is synthesized by the reaction between gallium metal and Cl_2 gas. In the growth zone, Ga_2O_3 is grown by the reaction between GaCl and O_2. The standard growth temperature is 1000 °C. $SiCl_4$ is used as a dopant source.

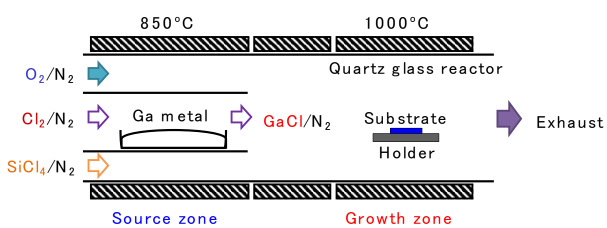
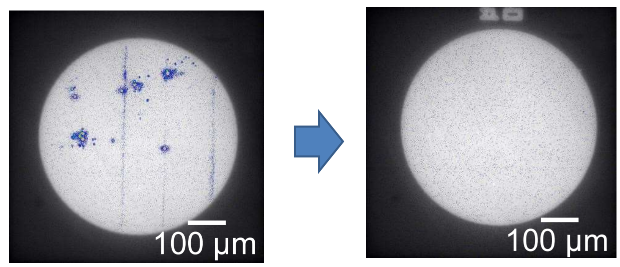


Fig. 3. Schematic illustration of β-Ga_2O_3 HVPE system.

In 2017, NCT fabricated 2-inch HVPE system. However, the HVPE epi had many killer defects around 200 /cm^2. The density of defects should be less than 1 /cm^2 in order to make a large current (over 10 A) device. One of the origins of these killer defects is polycrystalline particles of Ga_2O_3 generated during HVPE epi-growth. Subsequent improvements to the growth conditions successfully decreased these defects.

Figure 4 shows the results of emission microscopy. Emission microscopy is an observation method for identifying leakage points, in other words the locations of killer defects. In this case, the back side of the anode electrode was observed through the β-Ga_2O_3 epi wafer. Figure 4 (a) and (b) show emission microscopic images of SBDs fabricated with the conventional epitaxial method (epi) and with the improved method. The size of the anode was 500 μm, and the anode bias was set at -200 V. As can be seen, the conventionally made SBD had many emission points and line-like emissions. On the other hand, the SBD made with the improved method showed no such emissions.



(a) (b)

Fig. 4. Emission microscopy images of φ500 μm anode Ga_2O_3 SBDs made by (a) conventional epi and (b) improved epi.

β-Ga_2O_3 SBDs with a large 10-mm-square anode were fabricated to evaluate the killer defect density. Figure 5 shows a photograph of β-Ga_2O_3 SBDs fabricated on a 100-mm β-Ga_2O_3 epi wafer. The epi thickness and donor concentration were about 10 μm and 1×10^{16} /cm^3, respectively. Figure 6 shows (a) the reverse and (b) the forward characteristics. Clear forward and reverse characteristics were obtained. Maximum applied reverse voltage was fixed at -200 V, because these SBDs have no edge termination. About 52% of the devices (16/31 devices) had characteristics matching the theoretical prediction. From the yield and anode diameter, the killer defect density was estimated to be 0.7 /cm^2.

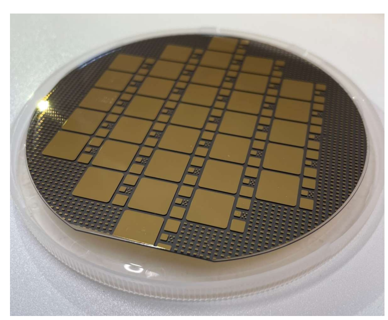
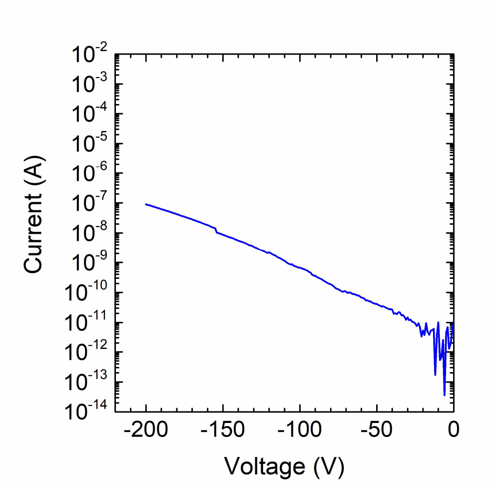
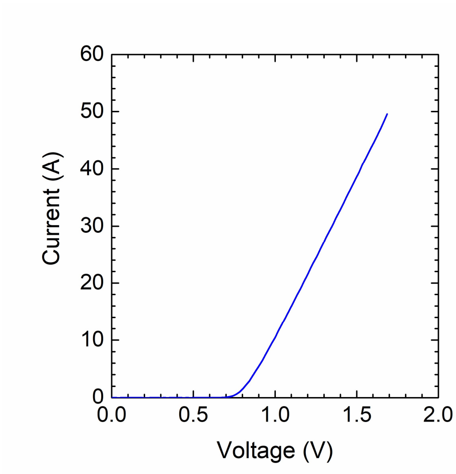


Fig. 5. Photograph of 10 mm square SBDs on a 100-mm β-Ga_2O_3 epi wafer.



(a)

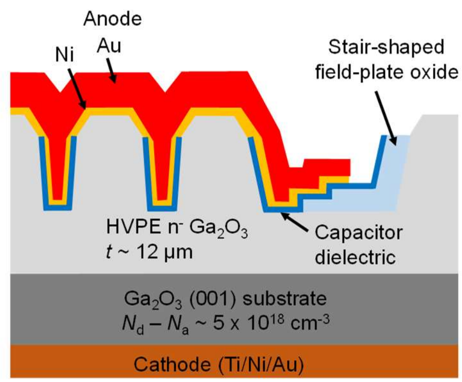


(b)

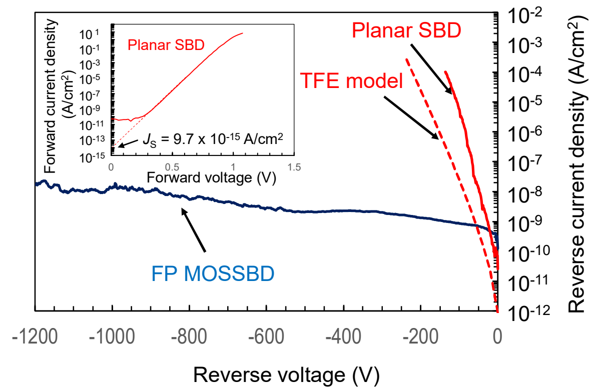
Fig. 6. (a) reverse and (b) forward characteristics of 10 mm square SBDs on a 100-mm β-Ga_2O_3 epi wafer.

β-Ga_2O_3 SBDS

In 2022, NCT reported the characteristics of 1.7-mm square 1.2 kV β-Ga_2O_3 MOSSBDs [6]. A stair-shaped field plate and a high-quality 2-inch Ga_2O_3 epi wafer were used, as shown in Fig. 7(a). Figures 7 (b) and (c) show the reverse and forward characteristics. The blue line indicates the characteristics of 1.7-mm square SBDs with a trench MOS structure and red line those of SBDs without the trench structure. The MOSSBD showed a high breakdown voltage of over 1.2 kV with sufficiently low leakage current. The ideality factor was about 1.05, and the specific on-resistance was about 13-17 mΩcm^2.



(a)



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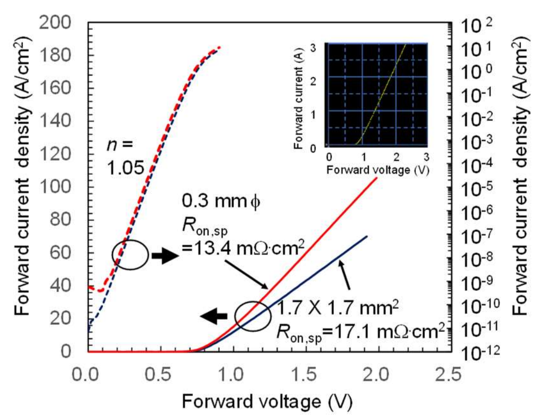
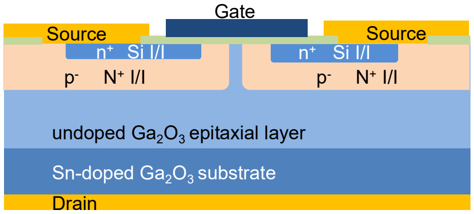


(c)

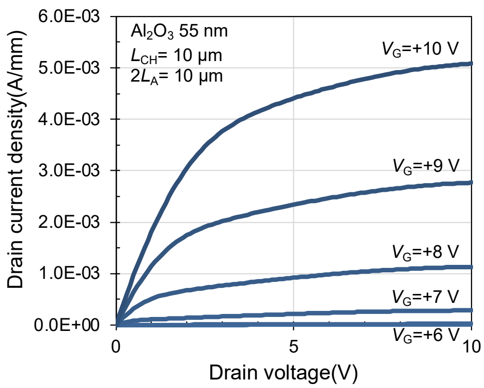
Fig. 7. (a) schematic illustration of 1.2 kV β-Ga_2O_3 MOSSBD, (b) reverse and (c) forward characteristics of β-Ga_2O_3 MOSSBD (blue line) and planer SBD (red line).

β-Ga_2O_3 FETS

In 2022, NCT developed normally-off β-Ga_2O_3 DMOSFETs. Figure 8 (a) shows the schematic illustration. p^--well or n^+-contact region were fabricated by nitrogen or silicon ion implantation technique. Figure 8 (b) shows drain current-voltage characteristics. The nitrogen concentration is set at 1×10^{18} /cm^3.The threshold voltage or specific on-resistance are about 6.6 V or 153 mΩcm^2, respectively. Figure 8 (c) shows the nitrogen concentration dependence of field effect mobility. The highest mobility of about 44 cm^2/Vs was achieved with nitrogen concentration of 1×10^{18} /cm^3. Figure 9 shows three-terminal off-state voltage waveform. The breakdown voltage increases with increasing nitrogen concentration. 1 kV was obtained with nitrogen concentration of 6×10^{18} /cm^3.



(a)



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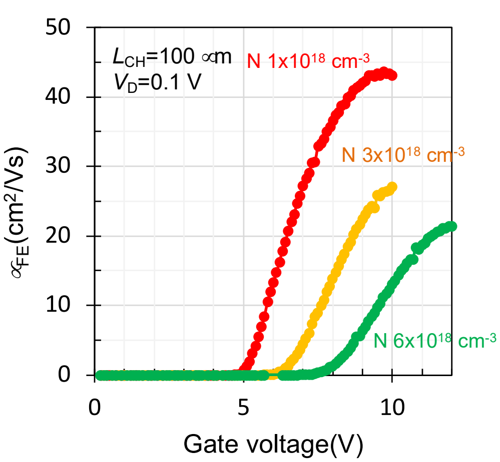

(c)

Fig. 8. (a) schematic illustration, (b) drain current-voltage, or field effect mobility characteristics of β-Ga_2O_3 DMOSFET.

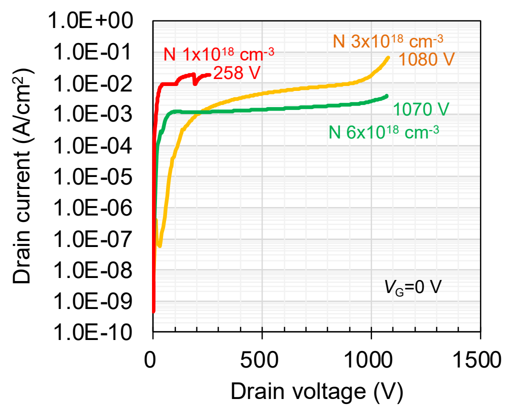

Fig. 9. Three-terminal off-state voltage characteristics of β-Ga_2O_3 DMOSFET.

CONCLUSION

Recent progress in β-Ga_2O_3 crystal growth or power devices was explained. Improvements to the crystal quality of 100-150 mm β-Ga_2O_3 wafers are underway. The development of β-Ga_2O_3 SBDs and FETs is accelerating. We hope to further development toward early commercialization of β-Ga_2O_3 power devices.

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