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Evolution and Prospects of Gallium Oxide-Based Materials and Power Devices

Shizuo Fujita

Kyoto Univ.
Katsura, Nishikyo-ku
Kyoto 615-8520, Japan
Phone: +81-75-383-3075 E-mail: fujitasz@kuee.kyoto-u.ac.jp

Abstract

Gallium oxide (Ga_2O_3) is now recognized as one of the promising semiconductors for power device applications owing to its ultra-wide band gap. This author reviews the fundamental properties, recent achievements, and future prospects of this material. The emphasis is given to the polymorphous of Ga_2O_3 and the discussion will be focused on β- and α-Ga_2O_3, which are attractive by the fact that solution-grown substrates are available and that the use of sapphire allows inexpensive devices, respectively.

1. Introduction

It has been well recognized that the breakdown electric field of a semiconductor tends to be higher for those with wider band gap energies, leading to lower on-resistance of devices. From this point of view, Ga_2O_3 is considered to be a potential material for high performance power devices, being supported by the ultra-wide band gap energy of 4.2-5.3 eV. In this presentation, the author will review the device-oriented research of this attractive material, which has made marked progress in these ten years, and point out the up-to-date research results of the advancement. We are pleased to introduce our recent results on corundum-structured Ga_2O_3 materials and devices.

2. Polymorphous of Ga_2O_3

Ga_2O_3 takes at least five different phases named α, β, γ, δ, and ε, as shown in Table I. Among them, β-Ga_2O_3 is the most stable one. It is noteworthy that β-Ga_2O_3 bulk substrates have been grown by conventional solution methods and this is in contrast to SiC and GaN which need particular technology for the bulk growths. It is the marked advantage that the device research can be started from the earliest stage with homoepitaxy. On the other hand, the crystal structure of β-Ga_2O_3, i.e., β-gallia structure, is characteristic to β-Ga_2O_3 and is scarcely seen for other materials. This is against the formation of a variety of alloy materials with different band gaps as well as heterostructures. α-Ga_2O_3 takes the corundum structure, which is common to a lot of materials including α-Al_2O_3 and α-In_2O_3, allowing the wide range of band gap engineering. However, the issues lie in how to grow high-quality metastable α-Ga_2O_3 by heteroepitaxy on sapphire. ε-Ga_2O_3 is expected to show piezoelectric polarization, leading to 2DEG at the heterostructure like the AlGaN/GaN system.

3. Evolution of β-Ga_2O_3 materials and devices

β-Ga_2O_3 bulks were developed as substrates of GaN LEDs [1] because β-Ga_2O_3 can be sufficiently low resistive and transparent to blue light. Homoepitaxial grwoth by MBE was demonstrated but the growth rate was too low on the substrate of (100) orientation [2,3]. Semiconducting property of β-Ga_2O_3 was evidenced by the formation of Schottky diodes and selective detection of deep UV light [4].

Later, it was shown that the homoepitaxial growth rate by MBE was increased to be >0.1 μm/h by applying the substrates of (010), (001) and other orientations as well as that the Sn doping allowed n-type conductivity control in the range of 10^{16}-10^{19} cm^{-3} [5]. Ion implantation was found to be effective for the formation of n^+ layers and ohmic contacts [6]. The demonstration of MESFETs and MOSFETs [7] firmly appealed the promising potential of Ga_2O_3 for power device applications.

The pioneering device achievement was followed by development of a variety of devices such as SBDs with trench MOS structure [8], normally-off MOSFETs [9], modulation-doped $(Al,Ga)_2O_3/Ga_2O_3$ FETs [10,11], and RF FETs showing g_m=21 mS/mm, f_T=3 GHz, and f_{max}=12.9 GHz [12].

More recently, HVPE was also found to be a promising technology for high-quality Ga_2O_3 layers. At the present stage, the author believes that Ga_2O_3 layers of the best quality have been grown by HVPE, as highlighted by the undoped carrier concentration of less than 10^{14} cm^{-3} [13]. The recent achievements includes depletion-mode vertical trench MOSFETs by using n^+ contact and n^- drift layers [14].

4. Evolution of α-Ga_2O_3 materials and devices

The growth of metastable α-Ga_2O_3 on sapphire substrates was demonstrated by the use of mist CVD [15]. The mist

Table I Crystal structure of Ga_2O_3.

Phases	α	β	γ	δ	ε
Thermal stability	metastable	stable	metastable	metastable	metastable
Crystal structure	rhombohedral corundum	monoclinic β-gallia	cubic defective spinel	cubic bixbyite	hexagonal
Examples of compounds of the same structure	Al_2O_3		$MgAl_2O_4$	c-In_2O_3	GaN

Table 2 Fundamental properties of β- and α-Ga_2O_3

Phases	β-Ga_2O_3	α-Ga_2O_3
Crystal structure	monoclinic, β-gallia structure	rhombohedral, corundum structure
Band gap	4.4 – 4.9 eV	5.2 – 5.3 eV
Substrate	β-Ga_2O_3 (n^+, insulating)	sapphire (insulating)
Growth	homoepitaxy	heteroepitaxy
Growth temperature	> 700 °C	< 600 °C*
Thermal stability	stable	metastable; transition to β-Ga_2O_3**
Alloys and heterostructures	limited	α-$(Al,Ga,In)_2O_3$
P-type material	under development Mg, Zn, N, etc. may act as acceptors in β-Ga_2O_3 p-NiO/n-Ga_2O_3 reported	α-Ir_2O_3, α-$(Ir,Ga)_2O_3$, and other corundum-structured p-type oxides doping under development
Device structure	lateral, vertical	basically lateral; vertical reported
Initial marketing strategy	ultra-high voltage high temperature high radiation	inexpensive devices low voltage (home appliances)

* Recently we achieved the growth of α-Ga_2O_3 at 700°C by modifying precursors [19].
** The transition temperature can be highered by introducing slight Al [20].

CVD is a simple and cost-effective growth technology where a water solution of source chemical(s) containing the metal element(s) is ultrasonically atomized and the mist particles formed are transferred to the reaction area to fabricate the target film with chemical reaction with oxygen.

The successful growth of α-Ga_2O_3 on sapphire by mist CVD was followed by n-type doing, band gap tuning by α-$(Al,Ga)_2O_3$ and α-$(In,Ga)_2O_3$ alloys, and formation of heterostructures [16]. FLOSFIA Inc. developed α-Ga_2O_3 SBDs with record-low on-resistance [17] and the TO220-packaged SBDs showed fast switching characteristics and reasonable heat resistance comparable to an actual SiC SBD device [18]. Since α-Ga_2O_3 devices are fabricated by mist CVD on sapphire substrates and the device size can be small owing to the low on-resistance, the device cost will be markedly low. The α-Ga_2O_3 power devices, therefore, may be accepted even for home appliances in which SiC and GaN devices are hardly used due to their high cost.

5. Prospects of Ga_2O_3 power devices

Both β- and α-Ga_2O_3 will be future developed as evolutional materials allowing high performance power devices. Table II compares fundamental properties of β- and α-Ga_2O_3. Homoepitaxial growth on β-Ga_2O_3 substrates offers ideal device structures without generation of dislocation defects during the epitaxial growth. β-Ga_2O_3 can be processed by Si-compatible ion implantation and dry etching. Selective area growth was also available. Rapid progress of β-Ga_2O_3-based devices is indebted to those features. α-Ga_2O_3 can offer inexpensive devices by the use of sapphire substrates but one cannot escape from defects formation in the epitaxial layers. Efforts have been focusing on ELO and buffer layers [21]. Formation of p-type layers is a common key issue for Ga_2O_3 devices, but we should note that we do not require p^+ layers like lasers. Fuji Keizai Group published the report predicting the future market of power devices, showing that the world-wide market of Ga_2O_3 devices will 145 billion JPY in 2030. This is almost 40% of that of SiC+GaN devices [22].

6. Conclusions

World-wide competition of the device-oriented research has been and will be continuing, leading to marked evolution of Ga_2O_3 devices. Of course, we need to overcome so many issues especially like reliability and cost, but the author is confident that we can meet the bright bloom of the Ga_2O_3 world supporting the future sustainable society.

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