

The Electrical Properties of Schottky Barrier Diode Structures Based on HVPE Grown Sn Doped Ga₂O₃ Layers

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Article history

Received February 21, 2022
Received in revised form
March 01, 2022
Accepted March 10, 2022
Available online March 31, 2022

Abstract

We report on the analysis of the electrical properties of Schottky barrier diode structures based on gallium oxide (Ga₂O₃). Ga₂O₃ has been grown by chloride-hydride vapor phase epitaxy on Al₂O₃ substrate. Samples with different amounts of Sn impurity are experimentally characterized. Surface and cross-sectional scanning electron microscopy images, X-ray diffraction patterns and current-voltage characteristics of Ga₂O₃ layers both with and without contact pads are presented. The value of the Ga₂O₃ optimal doping is determined and the parameters of the surface treatment that is performed before the contact pads deposition are established.

Keywords: UWBG semiconductors; Gallium oxide; Scanning electron microscopy; X-ray diffraction; Schottky diode

1. INTRODUCTION

Nowadays, there is a noticeable increase in research of semiconductors with an ultra-wide band gap (UWBG) such as AlGaN, diamond, Ga₂O₃, etc. [1–7]. UWBG semiconductors have visible prospects of applications for power electronics and optoelectronics due to their unique properties including high critical breakdown electrical field [8].

Gallium oxide is of great interest because of the value of band gap E_g from 4.5 to 5.3 eV [11,12] and high critical breakdown field, which for an unalloyed Ga₂O₃ reaches 8 MV/cm [13]. Gallium oxide has 5 phases: α , β , γ , δ , $\epsilon(\kappa)$; the most thermodynamically stable one is β -Ga₂O₃, the phases α - and $\epsilon(\kappa)$ -Ga₂O₃ can be made in the metastable state as thin layers deposited on a substrate [9,10]. First prototypes of α -, β -, $\epsilon(\kappa)$ -Ga₂O₃-based devices were already fabricated for power electronics and optoelectronics applications thus establishing a promising direction for the industry development [15–17].

In Ref. [17], the design for Schottky barrier diode (SBD) based on Ga₂O₃ was proposed. The design included Pt/Ti/Au anode on the front side of the sample to form

Schottky contact, an active region of unintentionally doped (Si doped for n-type conductivity) monocrystalline β -Ga₂O₃ and Ti/Au back side cathode to form ohmic contact. In Ref. [18], a similar structure was presented, however, a drift layer was added under the Schottky contact. This layer was also doped with Si. In Ref. [19], the authors considered the variant of design for SBD based on gallium oxide, where epitaxial layer Ga₂O₃ was used as a drift layer.

There are several problems when fabricating electronic devices based on Ga₂O₃ layers, such as control of optimal growth conditions, doping, layer thickness, etc. Manufacturing Ga₂O₃-based devices faces the challenge of creating contacts that requires improving not only contact material adhesion and electrical stability, but also reducing contact resistance [21].

In this work, we report on the growth by hydride vapor phase epitaxy (HVPE) Sn doped Ga₂O₃ layers on Al₂O₃ substrates. We describe structural and electrical characteristics of Ga₂O₃/Al₂O₃ samples suitable for SBD fabrication and measure the electrical properties of the designed samples with Schottky contacts.

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2. MATERIALS AND METHODS

A gallium oxide layers were grown on *c*-plane of α - Al_2O_3 substrates at atmospheric pressure using a horizontal HVPE reactor. The source of Ga in the growth process was inorganic compound GaCl, which was delivered to the growth zone by an inert gas and oxidizer O_2 . GaCl vapor was formed because of the reaction of HCl or Cl_2 gases with metallic Ga at growth temperatures. The growth was limited by mass transfer and, consequently, it was increased with the partial pressure of the GaCl or HCl/ Cl_2 source in the reactor. The method provides layers at a sufficiently high growth rate, $70 \mu\text{m/h}$ depending on the growth conditions [22].

Gallium oxide was doped in a single technological process at a growth temperature (Table 1). Sn was used as an alloying impurity. A sample of Sn was placed in a boat. The gas flow captured the Sn atoms and transferred them to the reactor. The amount of dopant was controlled by changing the carrier gas flow.

The structure of β - Ga_2O_3 layers was analyzed by means of X-ray diffraction (XRD). A DRON-8 (Burevestnik) X-ray diffractometer in a slit configuration with LLF X-ray tube with a copper anode and a NaI(Tl) scintillation detector was used in these studies. The morphology of the layers was analyzed using scanning electron microscopy (SEM) MIRA 3 (TESCAN) with the accelerating voltage of 5–30 keV. The concentration of impurities was measured using energy dispersive X-ray spectroscopy with Aztec (Oxford Instruments) equipment.

Polishing was used to obtain better adhesion of the metal to the surface of the epitaxial layer. Ga_2O_3 surface was polished using polishing machine and diamond abrasive paper with a grain size of $0.05 \mu\text{m}$ for 5 minutes. Polishing was carried out parallel to the sample plane.

To obtain the structure of Schottky barrier diode, contact pads with a width of 1 mm were applied along the entire sample (sample size $3 \times 3 \text{ mm}$) of Au to create a Schottky contact (electron affinity for Ga_2O_3 equals 4 eV, work function for Au is 5.23 eV), and of In to obtain a pseudo-ohmic contact (work function for In is 4.09 eV) [23]. Gold contacts were applied by cold magnetron sputtering. The Q150T Plus (Quorum Technologies) spraying unit ensured uniform spraying the Au. The

Table 1. Technological parameters of the growth [22].

Parameter	Value
Substrate material	α - Al_2O_3 (0001)
Growth temperature, °C	650–850
Carrier gas flow, l/min	6
Air flow, l/min	2
Precursor flow, cm^3/min	600

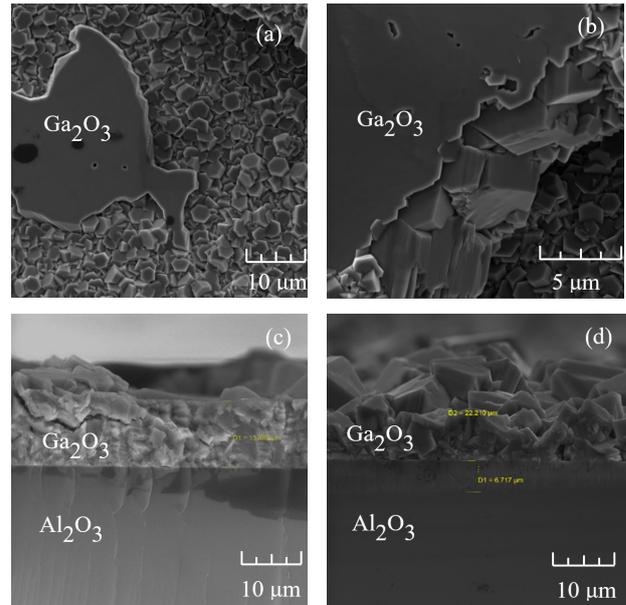


Fig. 1. SEM images of the surface (a, b) and cross-section (c, d) of the epitaxial Ga_2O_3 layer. The coalescence zones present in all images confirm the Stransky-Krastanov growth mechanism of the epitaxial layer. (a) A close-up of the area with a partially formed homogeneous layer; (b) a close-up of the boundary of the formation of a homogeneous layer; (c) the first cross-sectional area for sample 1; (d) the second cross-sectional area for sample 1.

indium contacts were applied using a soldering station. Pure In (99.999%) was used.

The I-V curves were measured using the two-probe method. Tungsten needles were installed on the surface layer of Ga_2O_3 layer (the distance between the probes is 1 mm). The data were obtained using Keithley 2601 (Tektronix) measuring device. Repeated measurements of I-V curves were obtained when the probes were installed on the contact pads.

3. RESULTS AND DISCUSSION

The production of electronic devices requires high-quality monocrystal Ga_2O_3 layers with a thickness of several microns [24]; our structure shows a layer thickness of $10 \mu\text{m}$. SEM studies demonstrate that the epitaxial layers grew according to the Stransky-Krastanov mechanism of growth due to high layer and substrate lattices mismatch that is consistent with data given in Ref. [25]. Such mechanism may be related to the granular structure of Ga_2O_3 . At insufficient temperature and (or) with a short-term process a homogeneous layer fails to form (coalescence does not occur), and separate “islands” are observed. Fig. 1 presents the confirming images.

The samples under investigation with their properties are described in Table 2. The geometric features of the samples were studied by SEM. According to the images

Table 2. Studied samples.

Sample number	Crystal structure of Ga ₂ O ₃ layer	Substrate	Impurity concentration in a layer, at/cm ³
1	β	α-Al ₂ O ₃	10 ¹⁷
2	ε + α	α-Al ₂ O ₃	10 ¹⁸
3	β	α-Al ₂ O ₃	10 ²⁰

(Fig. 1), the surface is quite heterogeneous. Layer demonstrates crystal grains fusing together. SEM images of the samples cross-section clearly show that homogeneity of the layer was achieved only in small areas.

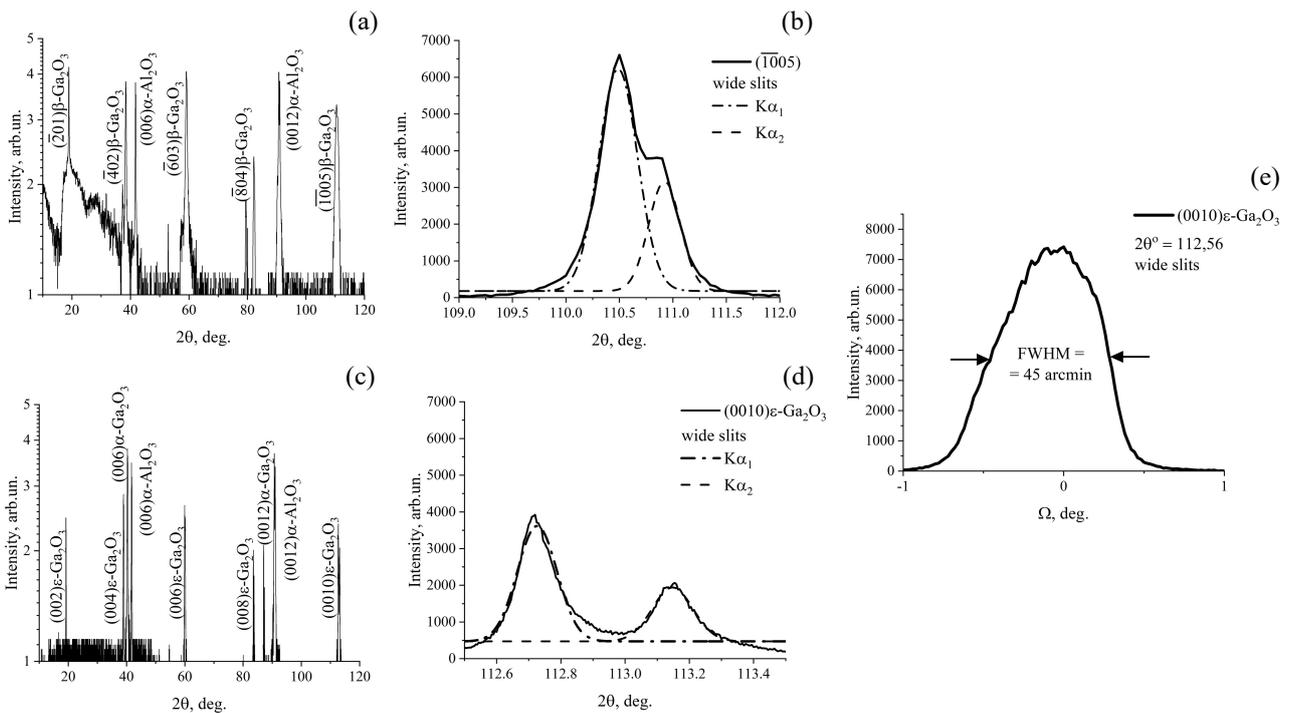
XRD completed the study of structural features on SEM. Figure 2 shows the XRD data for the Ga₂O₃/Al₂O₃ heterostructure. The semi-logarithmic scale on diffractograms was used to show that the grown layers demonstrate a relatively high purity of the phase composition and an insignificant number of undesirable intermetallic compounds and other compositions. The typical values of full width at half maximum (FWHM) for the long-range order reflections of Ω-scan rocking curves for experimental Ga₂O₃ layers were about 45 arcmin, that indicates the high crystal quality of the layers. For alloyed HVPE layers, the FWHM of rocking curve is about 45 arcmin. In XRD analysis in Ref. [24], the plane (004) for the epsilon phase is considered, this is the second order of reflection. In our case, the samples are doped and the increase in FWHM for the long-range order reflection curve is quite natural.

The main characteristic of epitaxial layers and the further development of diode structures is the dependence of current on voltage. Figure 3 contains the results of I–V

curves measurements of samples immediately after growth without additional processing. Voltage at knee — the opening voltage of the diode, this voltage differs depending on the amount of doping. U_0 equals 0.9 V for sample with average doping. The dotted lines indicate a current of 3 μA. The voltage values at a fixed current vary quite a lot. Changing the number of impurities leads to worse results. Therefore, a flow rate of doping impurity that does not lead to saturation is necessary.

To form Schottky and pseudo-ohmic contacts with better adhesion of the metal to the surface of the epitaxial Ga₂O₃ layer, polishing was used. Figure 4 shows the surface of epitaxial layers after polishing with a diamond disc. Demonstrated roughness is several times less than the size of the diamond crumb, that is necessary for forming contact pads.

The results of electrical measurements for SBD structure are given in Figure 5. Comparing I–V curves with and without contacts shows that the application of contact pads made it possible to increase the current up to 20 mA at a voltage of 5 V. Without contacts, the maximum current value at 5 V was 0.2 mA.


Fig. 2. Results of XRD studies of Sn doped Ga₂O₃ samples: (a) and (b) diffraction patterns for the β-Ga₂O₃ layer; (c) and (d) diffraction patterns for the (ε+α)-Ga₂O₃ layer; (e) rocking curve for (0010) plane of ε-Ga₂O₃ phase.

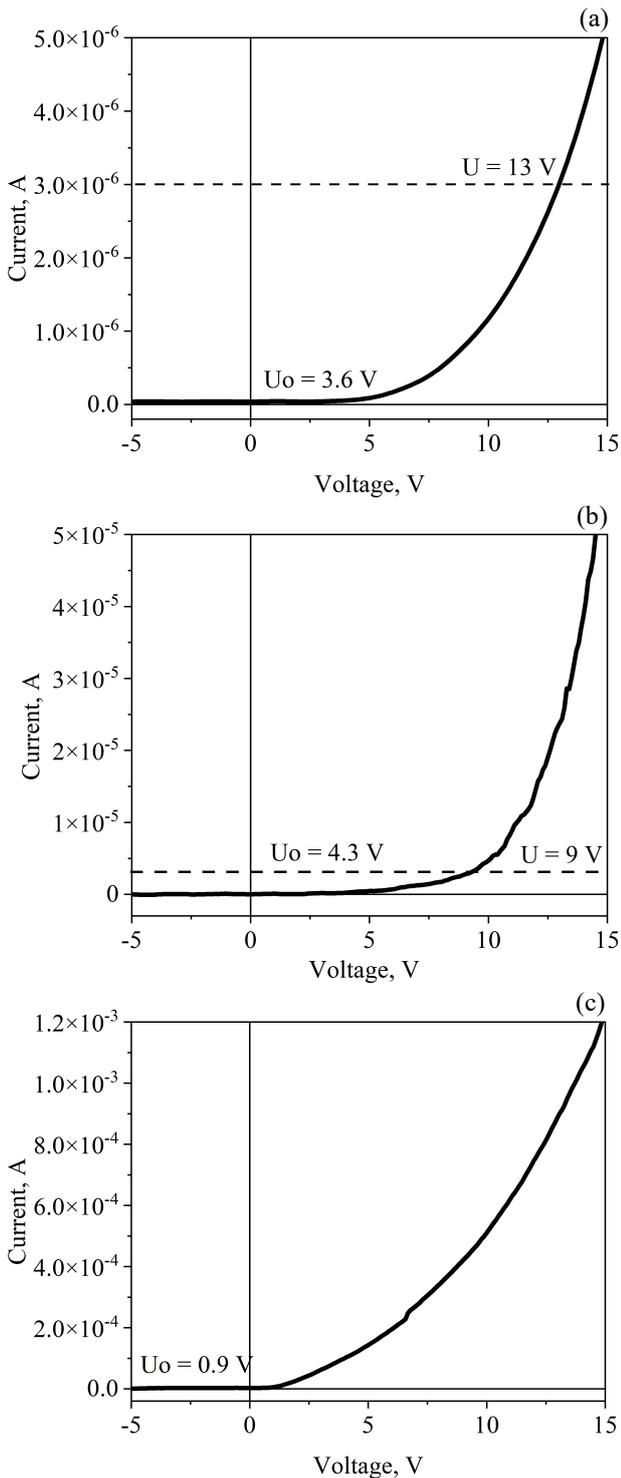


Fig. 3. I–V curves layers Ga_2O_3 for samples. (a) Sample 1, (b) sample 2, (c) sample 3

4. CONCLUSIONS

The HVPE Ga_2O_3 layers grown on Al_2O_3 substrates have been used as a basis for Schottky barrier diode structures. The structural quality of Ga_2O_3 layers was studied using scanning electron microscopy and X-ray analysis. It has

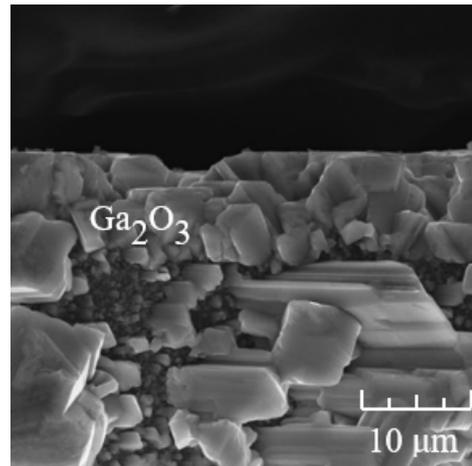


Fig. 4. SEM images cross-section of sample 2 after polishing.

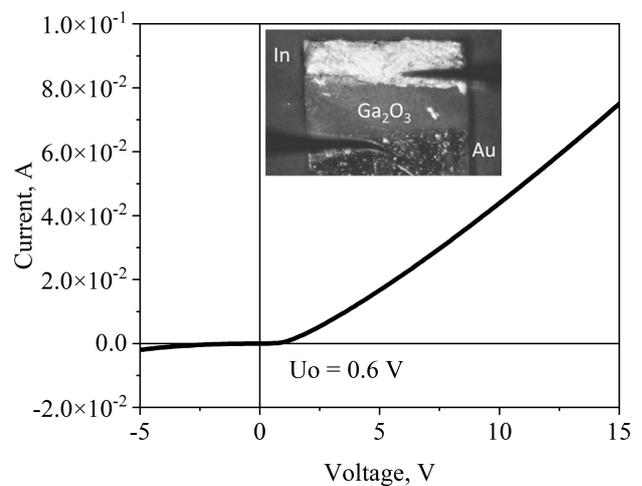


Fig. 5. I–V curves of the sample 2 SBD structure. The light strip in the inset is a pseudo-ohmic contact, the gray strip is an active layer of Ga_2O_3 , the dark strip with flashes is an Au Schottky contact, the cones are tungsten needles as probes.

been shown that the full width at half maximum of rocking curve increases with an increase in the degree of doping of the considered layers. It has been demonstrated that the grown Ga_2O_3 layers had a rough surface, therefore, mechanical polishing of the surface was used before wearing the contact pads — indium pseudo ohmic contact and gold Schottky contact.

The electrical properties of Ga_2O_3 Schottky barrier structure have been measured using the two-probe method. It has been shown that this Schottky barrier structure allows to receive a current of 20 mA at a voltage of 5 V. A complex dependence of electrical conductivity on the number of impurities has been found. Adding a lot of dopant impurities led to a deterioration in electrical conductivity. Thus, during the growth process, it is necessary to use such a flow rate of dopant impurity that does not lead to saturation.

Summing up all the above, this article presents the result of Ga_2O_3 HVPE layers growth, their structural

analysis, sample preparation, including mechanical polishing of the semiconductor layers, fabrication of Ga₂O₃ Schottky barrier structure and its electrical properties investigation. The data presented in this article will form the basis for the fabrication of next generation devices based on Ga₂O₃ Schottky barrier diode.

ACKNOWLEDGEMENTS

A.V. Kremleva and A.Yu. Ivanov received support from Russian Science Foundation Project No. 21-79-00211.

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УДК 621.315.592.3

Электрические свойства диодных структур с барьером Шоттки на основе эпитаксиальных пленок Ga_2O_3 легированных Sn

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Аннотация. Статья посвящена анализу электрических свойств барьерных диодных структур Шоттки на основе оксида галлия, выращенных методом хлорид-гидридной газофазной эпитаксии с использованием подложки Al_2O_3 . Для образцов с различным количеством примеси Sn исследованы: изображения поперечного сечения и поверхности, полученные методом растровой электронной микроскопии; рентгеновские дифрактограммы; вольтамперные характеристики слоев Ga_2O_3 , как с контактными площадками, так и без них. Определена величина оптимального легирования Ga_2O_3 и установлены параметры обработки поверхности перед нанесением контактных площадок.

Ключевые слова: широкозонные полупроводники; оксид галлия; растровая электронная микроскопия; рентгеновская дифракция; диод Шоттки