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Laser Processing of Gallium Oxide Crystals in the Preparation of Samples for Microelectronics

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Abstract

The paper presents the results of a study on an approach for sample preparation from bulk gallium oxide crystals using ablation laser cutting. The study was carried out using a «MicroSet» setup based on a fiber laser source with a wavelength of 1.064 µm and a power of 30 W. The possibility of processing material using a laser beam has been shown, the optimal trochoid width and pulse duration were selected, as well as the energy characteristics of the laser source and focusing optical system. The fundamental possibility of cutting gallium oxide crystals in different directions, regardless of the internal structure, the orientation of atoms and their bonds in the crystal lattice, has been shown.

Keywords: Gallium oxide; Laser ablation; Substrates; Sample preparation

1. INTRODUCTION

Today, gallium oxide, primarily its most stable phase β-Ga_2O_3, is a relatively new and promising material in the field of micro- and power electronics. In scientific literature, there are some works describing the process of creating MOSFET transistors with a breakdown voltage more than 2000 V [1–3] and high voltage Schottky diodes [4]. This is possible due to the unique physical properties of the β-Ga_2O_3 material, such as a large band gap (about 4.8 eV), a high breakdown electric field (8 MV/cm), a relatively high electron mobility (about 150 $cm^2/V \cdot s$) [5,6] and transparency in the visible and UV spectral ranges [7–9]. One of the advantages of gallium oxide is the possibility of manufacturing its own substrates [10] and, as a consequence, the possibility of autoepitaxy, which ensures the high perfection of device epitaxial structures based on β-Ga_2O_3.

However, serial production of substrates is currently limited not only by the amount of bulk crystalline material produced, but also by the complexity and high requirements of its further processing. This is due to the peculiarities of the crystal lattice of gallium oxide β-Ga_2O_3. The beta phase of gallium oxide belongs to the monoclinic system, space group C2/m [11] with lattice parameters a = 12.214 Å, b = 3.0371 Å, c = 5.7981 Å, β = 103.83°. The unit cell of the crystal has three different oxygen sites, designated O(1), O(2), and O(3), and two Ga sites, Ga(1) and Ga(2), as shown in Fig. 1.

The O(1) and O(3) nodes have the lowest coordination number of 3, which leads to weak interplanar bonds in the (100) and (001) planes (the so-called cleavage planes [12]). When subjected to mechanical action, the samples easily delaminate into thin plates parallel to the (100) plane, which significantly complicates mechanical processing, especially cutting of the material. Especially when processing small (up to 10 mm) samples. Fig. 2 shows a gallium oxide crystal after mechanical cutting. To solve this problem, a method of fixing the sample in epoxy resin is used [13] in order to minimize delamination of the samples along the (100) plane. However, the use of this method requires the introduction of an additional processing stage associated not only with fixing the sample in epoxy resin, but also its next release and cleaning.

A more promising and effective method of processing gallium oxide crystals to prepare experimental samples for research and analysis is laser cutting. The use of laser radiation, as well as cutting along a complex curvilinear contour, allows to exclude contact of the material with the

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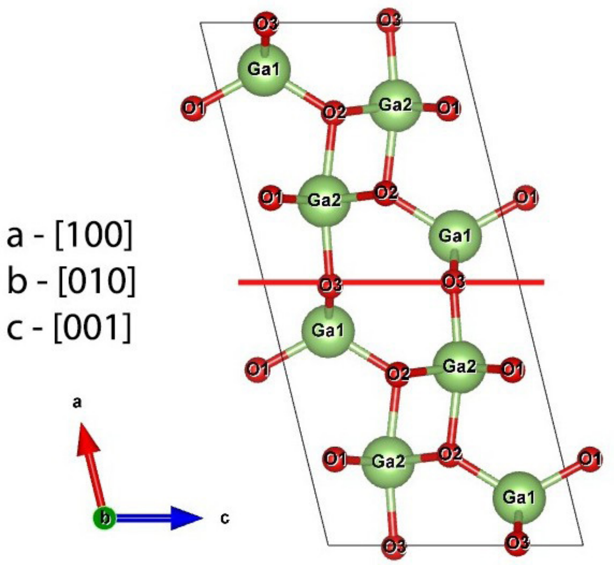

Fig. 1. Unit cell of β-Ga_2O_3. Cleavage plane (100) is shown in red, the thin black line indicates the bond of the unit cell. Image created in VESTA software (K. Momma and F. Izumi, Japan), lattice model obtained from the open electronic database The Materials Project (https://next-gen.materialsproject.org/).

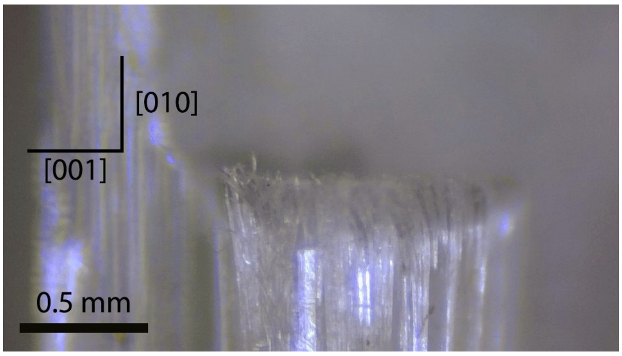

Fig. 2. An image of the end face of a mechanically cut β-Ga_2O_3 plate, illustrating the delamination of the sample along the (100) plane under mechanical action. The cut was made perpendicular to the (100) plane.

cutting tool and to divide the material without mechanical impact. The stability and variability of the range of laser radiation modes allows local action both on the entire thickness of the material and on the surface layers. This makes it possible to prepare samples of precise shape and size for various experiments.

The essence of the laser cutting method consists of transferring the energy of a laser radiation to the crystal lattice of a semiconductor, as well as the absorption of energy by free carriers and impurity atoms. Due to the received energy, local heating and evaporation of the material occurs (including bypassing the liquid phase when using ultra-short laser pulses), after which it is removed by a flow of gas or liquid [14]. This process is called laser ablation or ablative laser cutting [15].

Analyzing literary sources, one can notice that the issues of processing semiconductors, in particular silicon, gallium arsenide, gallium nitride, silicon carbide, etc., as well as crystals such as quartz, sitall, sapphire, in most cases are solved using various laser systems. Laser radiation can be used to manufacture a silicon anode for use in lithium-ion batteries [16]. The paper [17] shows the use of laser radiation for cutting sapphire (Al_2O_3) substrates. And the authors of the paper [18] not only separated epitaxial layers of gallium nitride into separate chips using laser action, but also scrubbed the epitaxial layer of gallium nitride.

Analyzing the work of the last decade on the interaction of laser radiation with matter, one can detect a tendency to shift the characteristics of the laser towards short and ultrashort pulse durations (pico- and femtosecond). So, the authors of the works [19,20] compared micro-, nano-, pico- and femtosecond laser radiation sources taking into account the rate of material removal during microperforation and came to the conclusion that laser systems with nanosecond pulse duration provide the highest ablation efficiency per unit of energy. In Ref. [21] the authors obtained surface diffraction structures using nanosecond radiation with a wavelength of 1.064 μm. This effect was achieved by controlling the melt in micron-sized areas. In works [22–24] the authors report on the successful selection of parameters for laser modification of the gallium oxide surface using femtosecond lasers

In this article, the authors provide the results of studying the cutting of bulk gallium oxide samples by using laser radiation and the possibility of using this method to obtain instrument-quality samples, which will subsequently allow the process of separating substrates with deposited structures into individual chips. This work is the authors' first experience in laser processing of gallium oxide. The task facing the authors in these experiments was to select the main parameters of laser radiation and cutting, ensuring a high-quality visual difference between laser and mechanical cutting.

2. MATERIALS AND METHODS

For laser processing experiments, bulk β-Ga_2O_3 crystals grown by the edge-defined film-fed growth (EFG) method were used. The crystal growing procedure is described in more detail in our previous publications [25,26]. To evaluate the technology of laser cutting from a bulk gallium oxide crystal using the method of chipping the sample along the cleavage plane (100), samples with a thickness of 0.8 mm and linear dimensions of about 70×15 mm were prepared.

The «MicroSet» installation (access to the installation was provided by the company «Laser Center», St. Petersburg, Russia) was used for laser cutting in the experiment with a laser radiation wavelength of 1.064 μm. The quantum energy of such radiation is 1.17 eV. The scanning system is equipped with a telecentric lens with a focal spot

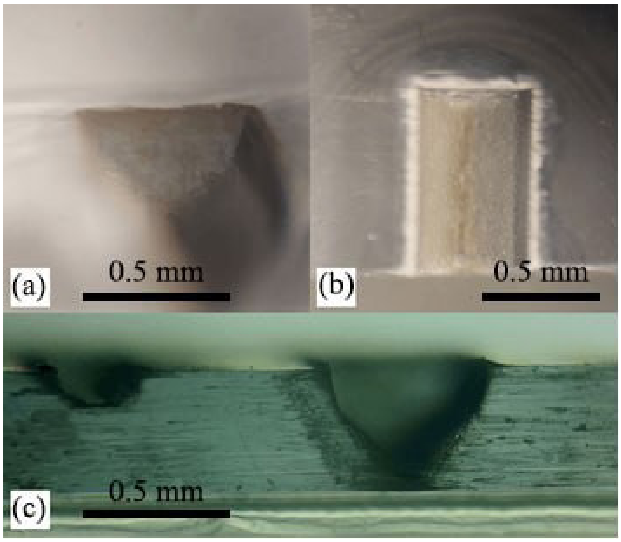

Fig. 3. Optical photographs of a laser-cut groove on the surface of a gallium oxide plate: (a) view of the back wall, (b) view from above, (c) view of the front edge.

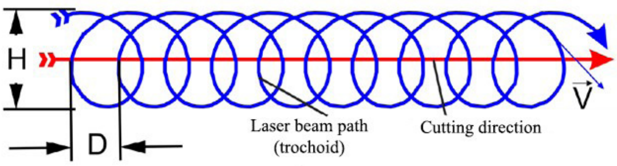

Fig. 4. Beam motion diagram, where *D* is the distance between the loops, *V* is the beam speed, *H* is the trochoid width (loop diameter).

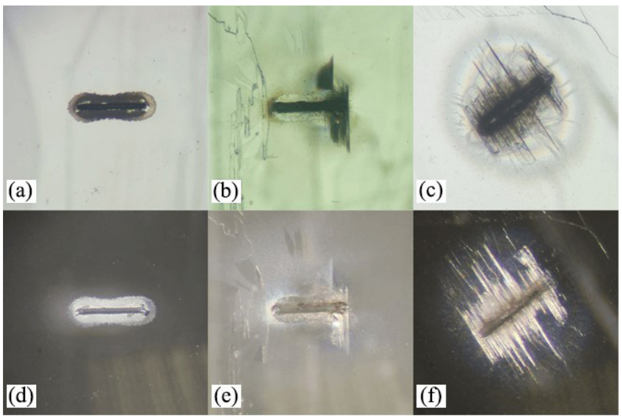

Fig. 5. Cracking of the material along the cut with increasing pulse duration. Pulse duration: (a,d) 100 ns, (b,e) 150 ns, (c,f) 200 ns. Illumination of the sample from below (a,b,c) and from above (d,e,f). For all cuts, the loop diameter $H = 0.2$ mm was used.

diameter of 30 µm. The scanning speed of the system is 15,000 mm/s. More detailed information about the installation can be found on the manufacturer's website [27].

3. RESULTS AND DISCUSSION

During the experiments it was found that the groove obtained after evaporation of the material has a prismatic shape (Fig. 3). The profile (section) of the cut is clearly visible in Fig. 3c. The obtained result differs from the prediction of the model, where the groove is obtained in the form of a cone.

Table 1. Processing modes.

P, %	V, mm/s	F, kHz	N	Δz, µm	H, mm	D, mm
100	40	99	37	4.75	0.4	0.01
100	40	99	37	4.75	0.35	0.01
100	40	99	37	4.75	0.3	0.01
100	40	99	37	4.75	0.25	0.01
100	40	99	37	4.75	0.2	0.01
100	40	99	37	4.75	0.1	0.01

To obtain the required quality of the cut, a special laser beam trajectory was selected, which has an uneven distribution of the laser radiation power density in relation to its coordinate position to prevent local overheating and cracking of the sample. A schematic representation of the trajectory is shown in Fig. 4.

During the experiment, the trochoid (loop) diameter varied in the range from 100 µm to 400 µm. The optimal loop diameter (*H*), which ensures minimal overheating and, as a consequence, minimal visually observable cracking along the cut at a given beam speed ($V = 40$ mm/s), was 200 µm. Table 1 presents data on the radiation power *P*, beam speed *V*, pulse repetition rate *F*, number of passes *N*, laser head displacement Δz per pass along the *Z* axis, loop diameter *H* and the distance between the loops *D*.

When studying cutting modes, it was found that at high pulse durations, cracking of the material along the cut occurs due to uneven heating and, as a result, uneven expansion of the material. Visually observable cracking was reduced to dimensions comparable to the cutting width by reducing the pulse duration to 100 ns. Images of the cuts and the accompanying cracking for pulses of different durations are shown in Fig. 5.

Thus, because of selecting the optimal parameters of the laser beam trajectory and pulse duration, samples of gallium oxide in the form of a circle and a square with geometric dimensions of 3×3 mm were obtained (Fig. 6). As can be seen in the photographs, with these parameters it is possible to cut the samples, and thermal cracking of the samples does not occur. Visually, the quality of the laser cut (Fig. 6b) is significantly higher than that of a similar mechanical cut (Fig. 2): there is no delamination or cracking near the cut, the edge (end) of the cut is much smoother.

4. CONCLUSIONS

The paper presents the results of an experiment on laser cutting of bulk gallium oxide and proves the fundamental possibility of using laser cutting technology to prepare

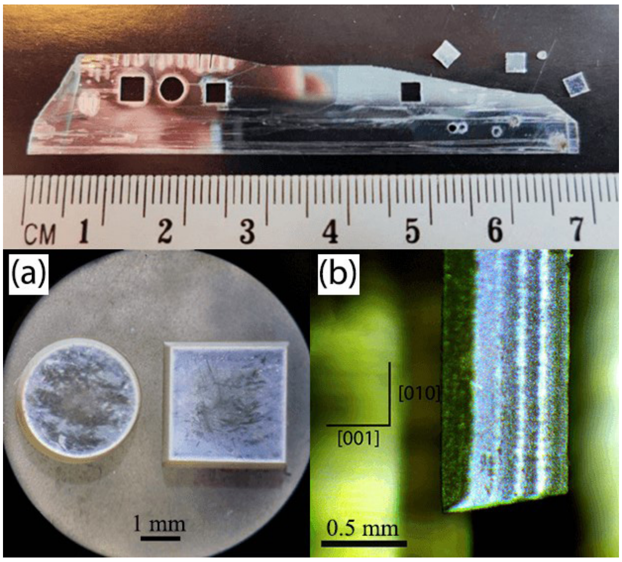

Fig. 6. Photographs of gallium oxide samples with dimensions of 3×3 mm and thickness of 0.8 mm prepared by laser cutting: (a) top view, (b) end view of the cut.

small-sized plane-parallel samples. The parameters of laser radiation and the trajectory of the laser beam were experimentally studied to prevent thermal cracking during the preparation of gallium oxide samples.

Further experiments aim to increase the cutting speed without loss of quality. It is also planned to conduct experiments to find suitable parameters for cutting crystals using pico- and femtosecond lasers.

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УДК 621.373.826

Лазерная обработка кристаллов оксида галлия при подготовке образцов для микроэлектроники

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Аннотация. В работе представлены результаты исследования подхода к подготовке образцов объёмных кристаллов оксида галлия методом абляционной лазерной резки. Исследование проводилось на установке «MicroSet» на базе волоконного лазерного источника с длиной волны 1,064 мкм и мощностью 30 Вт. Показана возможность обработки материала лазерным лучом, выбраны оптимальные ширина трохоиды и длительность импульса, а также энергетические характеристики лазерного источника и фокусирующей оптической системы. Показана принципиальная возможность резки кристаллов оксида галлия в различных направлениях, независимо от внутренней структуры, ориентации атомов и их связей в кристаллической решётке.

Ключевые слова: оксид галлия; лазерная абляция; подложки; подготовка образцов