Electrically Controlled Lenses based on GaN/AlN/SiC/GaN and Their Capabilities of Being Used in High-Temperature and Aggressive Environments

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Abstract: Possible application of the GaN/AlN/SiC/GaN-structures for manufacturing of active optical elements designed for operation in extreme conditions and, in particular, for investigation of oceanic hydrothermal sources (the "black smokers") is considered in the research. Advances in epitaxial III-nitride technologies in terms of obtaining "thick" AlN-layers and multilayer heterostructures make it possible to formulate a new approach to creating electrically controlled lenses, in which the longitudinal piezo effect (in the direction of the optical axis) is assumed to be implemented. In contrast to the radial-oriented transverse piezo effect previously applied by scientists in order to create bending deformations in bimorph membrane-type microlenses, the proposed design uses thin transparent conducting GaN-layers as control electrodes. As a part of the stated concept, an algorithm is also developed, and simulations are performed in order to study changes in the magnitude and nature of the curvature of the outer GaN surface, depending both on changes in temperature and changes in control voltage. It is assumed that this design solution of the lens will allow for adaptive thermal compensation of its optical parameters with a possible change of ambient temperature in a wide range (up to 1000 ºC).

1 INTRODUCTION

Underwater geothermal sources, formed as a result of the hot mantle interaction with ocean water penetrating the crust through cracks, and known as "black smokers", are of exceptional interest, and not only from a geological point of view. Superheated geothermal water with a temperature of up to 400OC, under high pressure, enriched with sulfides of many metals and volcanic gases (hydrogen sulfide, ammonia, methane), is a favorable environment for the emergence of unique biocenoses without photosynthesis, where sulfides are consumed by chemosynthesizing bacteria and which, in turn, serve as the basis for unique ecosystems (mollusks, crabs, worms) (Zeppilli, et al., 2018; Zeng, et al., 2021; Yamamoto, et al., 2018). Studies of such ecosystems are largely based on the analysis of images delivered by underwater vehicles, so it is important to develop new optical systems for operation in high-temperature and aggressive environments.

At the same time, recent advances in epitaxial technologies for wide-gap materials (SiC, GaN, AlN) have stimulated research focused on creating autonomous robotic devices, including underwater ones, for operation under extreme temperature conditions.

Many years of work in the field of creating the element base of high-temperature SiC electronics led, as a result, to the creation of the first simple microcircuits, which, nevertheless, are operational at temperatures of up to 500ºC (Tian, et al., 2017; Kargarrazi, et al., 2018; Kargarrazi, et al., 2016; Spry, et al., 2018) and even up to 800ºC (Neudeck, et al., 2017) to the formulation of new approaches in the technology of obtaining integrated power devices (Ilicheva, et al., 2018). At the same time, work in the field of wide-gap III-nitrides made it possible to make significant progress in the field of building high-temperature functional electronics, which combines numerous and diverse sensors and micromechanical devices (Dong, et al., 2019; Gavrilov, et al., 2018; Umeda, et al., 2013), and research is also underway in the field of single-

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crystal integration of AlN sensors with matrix SiC structures (Panyutin, et al., 2020).

A natural continuation of this series could be creation of an element base for high-temperature optics (including those for operation in aggressive environments), which would be based on transparent functional materials to perform compensatory functions under thermal cycling conditions.

2 MATERIALS AND TECHNOLOGY

Taking into account that not only the exceptional thermal stability (>1500ºC), chemical indifference and high mechanical strength, but also the piezoelectric activity of AlN along the polar direction (Akiyama, et al., 2009), makes this material, along with SiC, extremely attractive for high temperature applications (Fraga, et al., 2014).

The recently developed HVPE (hydride-chloride vapor phase epitaxy) technologies make it possible to obtain sufficiently thick (>300 mcm) AlN layers (Kukushkin, 2019), which provides ample opportunities for their use in the manufacturing of flat optical elements, while the use of laser or ion micromachining technologies makes it possible to form curvilinear surfaces necessary to obtain various microlenses. Moreover, it is obvious that the possibilities of heteroepitaxy also make it possible to create bimorph elements for which only one of the materials is a piezoelectric, for example, SiC/AlN structures. At the same time, it is also obviously desirable to use lenses and multi-lens systems with electrically controlled characteristics, which would make it possible to level the negative effect of temperature changes on the quality of the formed image.

The technological implementation of such a structure (Figure 1) is possible, for example, using the epitaxial production of an AlN layer on a preformed curved surface of an insulating hexagonal SiC substrate, and the production of doped thin (<1 mcm) conductive GaN layers as external transparent electrodes (for more details, see (Panyutin, et al., 2019). Thus, the control voltage U0 applied to these GaN electrodes causes, in accordance with the inverse piezoelectric effect, a change in the local thickness of the bimorph SiC/AlN lens AlN layer and can be used to compensate for the size due to possible thermal expansion. However, a side effect of the AlN piezodeformation may cause the outer surface to deviate from the original sphericity. In this work, the main emphasis will be placed on the study of possible aspherization in the process of changing the control voltage, which is of undoubted interest for the development of tunable aspherical.

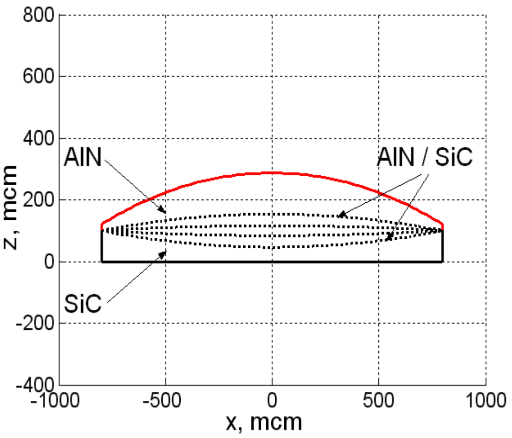

Figure 1: AlN/SiC lens profile for different variants of curvature of the internal heterointerface.

3 COMPUTER SIMULATION AND CALCULATION DETAILS

It is known that the equation of the sphere surface geodesic line in Cartesian coordinates for the section corresponding to y=0 can be represented as:

$$z(x) = z_o \mp \sqrt{R^2 - r_o^2} \pm \sqrt{R^2 - x^2} \qquad (1)$$

Here z is the coordinate of the lens surface, $2r_o$ is its diameter, R is the radius of the surface curvature, uniquely related to its focal length. Based on this formula, it is easy to obtain the dependence of the lens piezocomponent thickness w_2 for y=0 on the x coordinate:

$$w_2(x) = \sqrt{R_2{}^2 - x^2} - \sqrt{R_2{}^2 - r_o^2} + \dots$$

$$+\sqrt{R_1{}^2 - x^2} \mp \sqrt{R_1{}^2 - r_o^2} \qquad (2)$$

In accordance with Figure 1, here R_1 is the technologically specified sphere radius of the SiC/AlN heterointerface; R_2 is the radius of the AlN/GaN surface, which depends both on the external temperature T and on the external control voltage U_0. Then the thickness $w_1(x)$ of the composite lens “piezo-indifferent” component can be represented as

$$w_1(x) = d_o - \sqrt{R_1^2 - x^2} \mp \sqrt{R_1^2 - r_o^2} \quad , \tag{3}$$

where d_o is the thickness of the composite lens at $|x| = r_o$.

The voltage U_0 supplied from an external source to the GaN electrodes will be redistributed between the SiC and AlN dielectric layers

$$U_0 = U_{w1}(x, R_1) + U_{w2}(x, R_1) \tag{4}$$

and

$$U_{w2(x)} = U_0 \cdot \frac{w_2(x, R_1)}{w_1(x, R_1) + w_2(x, R_1)} \tag{5}$$

where $|x| = r$, and R_1 is included as a parameter. It can be shown that the change in the z-coordinate of the AlN surface with a change in the control voltage

$$\Delta z_2(x) = d_{33}^{AlN} \cdot \frac{\varepsilon_2 - 1}{4\pi} \cdot \frac{w_2(x)}{w_1(x) + w_2(x)} \cdot \Delta U_0 \tag{6}$$

where $d_{33}^{AlN} = 3.9 \cdot 10^{-9}$ mm/V [14] is the component of the AlN piezoelectric coefficient tensor and ε_2 is the permittivity.

The degree of surface asphеrization (i.e., its deviation from a spherical profile) can also be estimated by introducing the local curvature of the outer surface,

$$K(x, \Delta U_0) = \frac{\left|d^2z/dx^2\right|}{\left(1 + (dz/dx)^2\right)^{3/2}} \tag{7}$$

The family of curves demonstrating the deviation of the AlN surface from the sphere for different values of the radii of the AlN/SiC interface is shown in Figure 2.

The local radius of curvature of an aspherical surface is obviously not a constant and is defined as the reciprocal of the local curvature, i.e.

$$R_{asp}(x, \Delta U_0) = K^{-1} \tag{8}$$

The deviation of the surface from spherical can also be characterized by introducing the coefficient of relative asphericity

$$K_{Asp}(x, \Delta U_0) = R_{Asp} / R_{Sp} \tag{9}$$

Its dependence on the radius of curvature of the AlN/SiC interface (the case of positive values of the radius) is shown in Figure 3.

All calculations were made in the MATLAB.

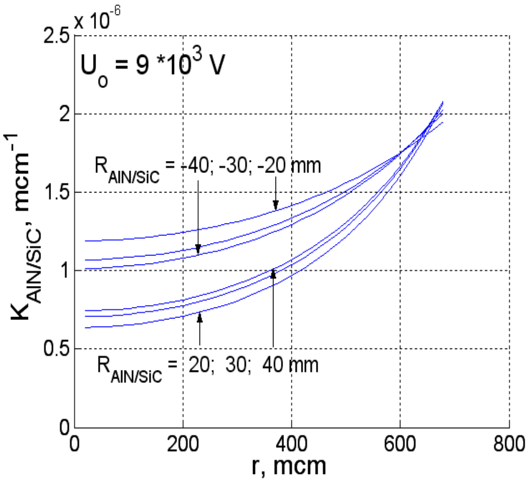

Figure 2: Radial dependence of the local curvature of the outer AlN surface for different curvature radii of the AlN/SiC boundary.

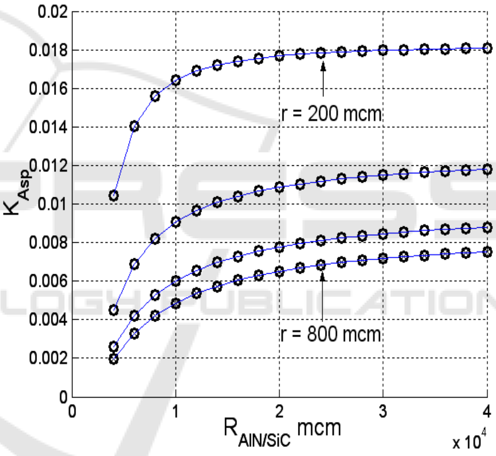

Figure 3: Dependence of the asphеrization coefficient of the AlN surface on the radius of curvature of the heterointerface.

4 CONCLUSION

New opportunities that open up in connection with the further improvement of technologies for obtaining high-transparency epitaxial quasi-bulk aluminum nitride and “thick” AlN/SiC heterostructures make it possible to develop new types of heat-resistant optical lenses with a controlled asphеrization function, which can be useful for the further development of multi-lens aspherical objectives.

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