Analysis of the possibility of creating an acoustic velocity sensor using GaN epitaxial films

Y Enns¹,², A Kazakin¹,², Y Akulshin², A Mizerov¹ and R Kleimanov¹,²

¹ Alferov University, 8 Khlopina, St. Petersburg, 194021, Russia
² Peter the Great Saint-Petersburg Polytechnic University, 29 Polytechnicheskaya, St. Petersburg, 195251, Russia

ennsjb@gmail.com

Abstract. This paper results in results of analyzing the possibility of creating an acoustic velocity sensor using epitaxial GaN films. Technology for the fabrication of a microelectromechanical acoustic velocity sensor was developed and a prototype of the sensor was produced. The simulation of the characteristics of the obtained acoustic velocity sensors was carried out on the basis of the measured electrical characteristics, where the sensitivity and the directional pattern were determined.

1. Introduction
Vibration control is of high importance for the diagnosis of industrial equipment, marine, aerospace and nuclear industries. The high number and density of equipment requires the creation of a distributed system of vibration sensors. The overwhelming majority of dangerous vibrations have frequencies in the audio range, therefore, acoustic velocity sensors have received great prospects for vibration diagnostics [1]. The sensors comprise a microelectromechanical system (MEMS) of two short, thin and closely spaced platinum beams that are heated to about 300 °C [2]. The resistance of the beams depends on the temperature. The action of the acoustic flow instantly changes the temperature distribution, forming a difference in resistance across the sensor beams. This difference in resistance is measured with a bridge circuit that provides a signal proportional to the acoustic flux. Despite the fact that these sensors are proven, their applying in harsh environments is very limited. Therefore, it is necessary to search for new materials that are stable during operation conditions of high temperatures and corrosive gases.

Due to its high chemical, temperature and radiation resistance, GaN is a promising material for electronics and sensors for harsh environments [3]. GaN sensitive elements can be used in miniature gas sensors, temperature and pressure sensors, thermal flow sensors and other MEMS. This work is aimed at creating a design and production technology for acoustic velocity sensors based on GaN epitaxial films.

2. Finite elemental analysis
The results obtained in the course of previous studies of the technology of fabrication microbeam elements, structural parameters and mechanical parameters, as well as the values of the temperature coefficient of resistance (TCR) and gauge factor (GF), show the possibility of creating a MEMS thermal sensor based on epitaxial GaN films. [4,5]. Methods of finite elemental analysis were used to
assess the performance of the developed design of thermoanimometers. The simulation was carried out in the COMSOL Multiphysics software. Estimation of the characteristics of the GaN anemometer required an interconnected solution to the problem in the mechanical and electrical domains, as well as in the areas of heat and mass flow. The effect of laminar airflow at low flow rates (up to 1 cm / s) on the sensor output signal was investigated taking into account the effect of the incident angle, i.e. flow velocity vector relative to the plane of thermoelements.

The GaN sensor model consists of two parallel planar beam elements 0.5 µm thick, 250 µm long and 20 µm wide. The beam elements are separated from the silicon substrate by a cavity of 50 µm and fixed at the ends (Figure 1). Such thin-film structures are characterized by the curvature of the profile of the beams after separation from the substrate. The profile of the beam can have a high impact on the distribution of gas flow rates in the vicinity of the threads. The profile was determined based on the previously obtained values of internal stresses for epitaxial GaN films [4]. The mechanical parameters were determined using a modulus of elasticity $E = 200$ GPa and internal stresses 1.39 GPa. It was determined that the magnitude of internal stresses leads to a tensile deformation of 0.006 and the formation of an arc-shaped profile with a deflection height of 12 µm.

The solution of interrelated problems was carried out by finding the self-heating temperature of the beams due to the flow of current through them and changing the convection conditions due to the action of the laminar flow. A potential difference for each of the beam elements equal to 35 V was set on the contact pads with one common ground output. The electrical conductivity parameters for epitaxial GaN layers were set from the previously experimentally determined temperature dependence [5]. In the model, an assumption was made about the ideal isolation of the epitaxial layer by the Si$_3$N$_4$ layer from the silicon substrate. At the bottom edge of the silicon chip, a fixed room temperature was set, which corresponds to the ideal heat dissipation from the sensor. The calculation of convective heat removal from the beam elements was carried out on the basis of the atmospheric gas flow in the laminar approximation. The flow rate was set at 10 cm / s. In this case, the incident angle of the flow with respect to the sensor was taken into account, which was set in the range from 5° to 95°.

The resistance of the beam elements for normal conditions and low power was 69 kΩ. Figure 2 shows the results of numerical modeling of the influence of the incident angle of the gas flow on the change in the resistance of the beams. It can be seen from the polar diagram that the maximum difference in resistance occurs at incident angle of about 45°. This is caused by the maximum displacement of the gas flow relative to the beam elements and the redistribution of the heating area (Figure 3). The results of finite elemental analysis show the possibility of creating a sensor that is selective in the direction of action of the air flow. However, it should be noted that the difference in resistance between the beam elements will also be proportional to the flow amplitude. This signal must be isolated using a non-vector flow velocity sensor.

![Figure 1. Acoustic velocity vector sensor prototype model.](image1)

![Figure 2. Dependence of the relative change of resistance on the incident angle.](image2)
3. Experiment

In this work, epitaxial n-type GaN films were grown on high-resistance Si (111) wafers (R > 10000 Ohm cm) by molecular beam epitaxy on a Veeco Gen 200 industrial setup equipped with a high-frequency (13.56 MHz) plasma source Riber RFN-50/63 [6]. Before growing GaN, silicon substrates were annealed at T = 850 °C to remove the SiO₂ film. The growth procedure began with the deposition of several Ga monolayers on the silicon surface to prevent SiₓNᵧ formation. Then an array of GaN nanocolumns was formed as a seed layer. To obtain a continuous GaN layer, the coalescence of GaN nanocolumns was carried out. In order to obtain continuous GaN layer the coalescence overgrowth of GaN nanocolumns was carried out. The samples have a fairly smooth surface morphology; the total GaN height is about 550 nm.

Postgrowth technology has been developed to form the micromechanical structures of the GaN velocity acoustics sensor. Gold platforms chrome adhesive layer were applied to the GaN layer by magnetron sputtering. This stage was followed by the application of a SiO₂ mask and the formation of a lithographic pattern. The topology of GaN beam heaters was formed using methods of anisotropic dry etching of a GaN layer on an Oxford Plasma Lab ICP 380 setup with a Cl₂ / BCl₃ based reactive plasma-chemical etching mode [7]. The release of micromechanical structures was carried out by isotropic etching of silicon to a depth of 50 µm in SF₆ plasma. The last step was dry removal of the silica mask. The length of the formed beam heaters was 500 µm, 0.5 µm thickness and 10 µm width.

The configuration of the prototypes produced was examined using a SEM Supra 25 Zeiss. The electrical characteristics were measured using a half-bridge circuit using the AKIP 4109/2 data acquisition system. Temperature measurements were carried out in the temperature range of 20 - 140 °C by heating the sensor chip with a Heraeus Pt6.8 M1020 microheater and controlling the temperature with a Pt-1000 microthermometer. The limiting values of the gas flow were measured by feeding a narrow flow from a micro-blower through a needle with a diameter of 1.2 mm.

4. Results and discussions

SEM of the produced prototypes is shown in Figure 4. After the release of the beam elements, an arcuate deformation was observed. The lifting height of the beams was 14 µm, which advises the design value.

![Figure 3. Temperature distribution under the flow rate of 10 cm / s.](image)

**Figure 3.** Temperature distribution under the flow rate of 10 cm / s.

![Figure 4. SEM image of a prototype acoustic velocity sensor.](image)

**Figure 4.** SEM image of a prototype acoustic velocity sensor.
The measured resistance under normal conditions was 60 kΩ. In this case, the absence of electrical insulation of the beam elements from the silicon substrate was observed. The silicon resistance was measured between contacts without beam elements and was 300 kΩ. Based on the obtained temperature dependences of the resistance of the sensor with and without beam elements, the measurement of the resistance of an individual beam was selected. The results of measuring the temperature dependence of the resistance of the beam are shown in Figure 5.

![Figure 5. Temperature dependence of the resistance of the beam element.](image)

5. Conclusion
The results of finite elemental analysis showed the fundamental possibility of creating an acoustic velocity vector sensor based on epitaxial GaN layers. The simulation of the characteristics of the obtained acoustic velocity sensors was carried out on the basis of the measured electrical characteristics, where the sensitivity and the directional pattern were determined. The developed technology of epitaxial layer growth and post-process has been successfully demonstrated. It should be noted that the problem of the lack of isolation of the working layer from the substrate can be solved using SOI plates.

Acknowledgments
This work was carried out in Alferov University and was supported by the Ministry of Education and Science of the Russian Federation (grant № FSRM-2020-0008).

References
[1] Guiot M, Comesaña D F and Pousa G C 2015 Proc. Inter-Noise 1-8
[2] Bree H-E, Leussink P, Korthorst T, Jansen H, Lammerink T S J and Elwenspoek M 1996 Sensors and Actuators 54 552
[3] Rais-Zadeh M, Gokhale V J, Ansari A, Faucher M, Cordier Y and Buchaillot L 2014 J. Microelectromech. Syst. 23 1252-71
[4] Enns Y, Kazakin A, Mizeroz A, Shubina K, Morozov I, Mokhov D and A Bouravleuv 2020 J. Phys.: Conf. Ser. 1695(1) 012019
[5] Kazakin A, Enns Y, Mizeroz A, Kleimanov R and Bouravleuv A 2019 J. Phys.: Conf. Ser. 1410 012214
[6] Timoshnev S N, Mizeroz A M, Sobolev M S and Nikitina E V 2018 J. Semiconductors 52 660
[7] Shubina K, Berezovskaya T N, Mokhov D V and Morozov I 2018 J. Semiconductors 52 2117