Optimization Problem of Thermal Field on Surface of Revolving Susceptor in Vapor-Phase Epitaxy Reactor

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Abstract. Nitrides of group III elements are a very suitable basis for deriving light-emitting devices with the radiating modes lengths of 200-600 nm. The use of such semiconductors allows obtaining full-color RGB light sources, increasing record density of a digital data storage device, getting high-capacity and efficient sources of white light. Electronic properties of such semi-conductors allow using them as a basis for high-power and high-frequency transistors and other electronic devices, the specifications of which are competitive with those of SiC-based devices. Only since 2000, the technology of cultivation of crystals III-N of group has come to the level of wide recognition by both abstract science, and the industry that has led to the creation of the multi-billion dollar market. And this is despite a rather low level of development of the production technology of devices on the basis of III-N of materials. The progress that has happened in the last decade requires the solution of the main problem, constraining further development of this technology today – ensuring cultivation of III-N structures of necessary quality. For this purpose, it is necessary to solve problems of the analysis and optimization of processes in installations of epitaxial growth, and, as a result, optimization of its constructions.

1. Introduction
The nitrides of a number of elements of the third group, representing such III-N materials as AlN, InN and GaN, are claimed today to have the same fundamental role that was played in due time by silicon.

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The nitrides of group III elements are presently grown with all modern epitaxial methods: metal organic vapour phase epitaxy (MOVPE), chloride vapour phase epitaxy (CE) and molecular beam epitaxy (MBE). These methods have their own peculiarities and allow obtaining various results. Chloride vapour phase epitaxy is characterized by high (up to several hundreds µm/h) growth speed. Besides, chloride epitaxy makes it possible to efficiently manage the growth process by changing the equilibrium in the processes occurring on the growing surface. Molecular beam epitaxy of nitrides is characterized by low (0.5-1 µm/h) growth speeds and not very high growing temperatures (~800°C). Metal organic nitride epitaxy became the primary method for the industrial production of device structures for fiber linear applications. The method proved to be very reliable in terms of gaining high-quality homogeneous layers of a large area, efficient growth processes management, precise control
over precipitation parameters, the possibility to dope film during the growing process, etc. The growth speeds typical of this method are ~ 1-3 µm/h.

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2. Research objective
The objective is to present analytical results of the optimization problem of growth processes of III-N materials in horizontal reactors of vapor-phase epitaxy with the rotating susceptor.

3. Metal organic vapour phase epitaxy of group III elements nitrides
Today metal organic vapour phase epitaxy (MOVPE) of group III elements nitrides is the main method for obtaining the device structures based on these materials. All key achievements of specific device characteristics, lower defect density, obtaining new device structures were gained by means of growth with this method. MOVPE successfully combines the advantages of both chloride and molecular beam epitaxy [1].

MOVPE uses metal organic compounds as sources of necessary group III elements. As a rule, in the nitride system such compounds are trimethylgallium (TMGa), triethylgallium (TEGa), trimethylindium (TMIn), trimethylaluminum (TMA1). Ammonia is used as a nitrogen source. Implantation is performed with monosilane SiH₄ to obtain an n-type conduction and biccyclopentadienyl magnesium Cp2Mg to get a p-type. Hydrogen, nitrogen and their mixtures are used as carrier gases. Growth temperatures are 900-1,100°C for GaN.

Typical speeds of growth for nitrides MOVPE are 0.1-1 nm/sec. This is higher than those of molecular beam epitaxy; however, they are quite low to provide a good control of thicknesses in the active area of devices. On the other hand, the growth speed ~1 nm/sec does not allow the growth of thick (~100 µm) buffer layers of GaN. Nevertheless, it is sufficient to obtain buffer layers with the thickness of ~5-6 µm.

In the simplest case, the MOVPE process represents feed of mixed chemical reagents in the gas carrier to the foundation layer heated up to the high temperature. Meanwhile, a chemical reaction occurs on the surface of the foundation layer leading to formation of a necessary compound. This process is accompanied by heating the gas and solid phase and mass transfer in the gas phase and on the surface of the solid phase. To get a full understanding of MOVPE, it is necessary to study gas flows in the reactor together with reaction behavior both in the gas phase and on the foundation layer surface with the account of thermal dynamics and kinetics of corresponding reactions.

4. Problem of synthesis of optimum design of elements of reactor
In case of MOVPE of group III nitrides, a relatively small change of conditions in the reactor (temperature, partial pressure values of ammonia, hydrogen and nitrogen) allows one to significantly manage the extent of the process equilibrium and optimize it for each of layers of the multiple layer structure. In its turn, this gives an opportunity to influence the formation of point and extended defects, self-compensation extent, achievable implantation levels, etc. [1, 2]. On the other hand, it is obvious that small deviations of conditions in the reactor lead to emergence of a large number of dislocations and nonuniformity of properties on the area of the grown-up structure.

The author investigated a number of industrial horizontal reactors of vapor-phase epitaxy of eddy-current heating with a rotary substrate holder. The analysis of the received results of pilot studies has allowed revealing a number of disadvantages of full-scale plants, eventually reflected in quality of cultivated structures. Considerable unevenness of distribution of the thermal field throughout surfaces of a vacuum jig and, as a result, a substrate belongs to the main problem. Prominent irregularity in the distribution of the thermal field on the surface of vacuum jig as a consequence base is related to the main problem.
So, it was found that nonuniformity in the distribution of temperature of the thermal field on the susceptor’s surface leads to a deviation of optical properties in terms of area of a crystal. The last are expressed including the change of the length of the radiation mode that, according to researches, composed 3 microns per each 1°C.

The causes of occurrence of the specified nouniformities were analyzed and it is established that they are connected first of all with a non-optimal configuration of a flow of the carrier gas and design defects of the inductor that ignore considerable influence of gas flow on the change of the thermal field on surfaces of the susceptor.

5. Influence of location of stagnation point of flow and change of its mode

Active scientific research on heat transmission from the revolving disc has been conducted over several decades. Such heighten interest in a problem is in relation with the fact that the systems containing revolving discs are used in gas-turbine [3, 4] and electrochemical installations, chemical reactors, in brakegears of transport, etc.

As of today, interest in this problem does not decrease as witnessed by the materials of a set of scientific and technical conferences and articles. In a limited number of cases, the stream over the spinning surface can be considered as the modified stream over a motionless surface provided that the observer is on the fixed surface that moves together with it.

However, the generally centrifugal effect or nature of the three-dimensional boundary layer cause formation of essential additional streams that can not be neglected. In the rotating systems, convective heat transfer exchange is in a complicated way connected with flow conditions. Therefore, in the aggregate, these two phenomena are the objects of scientific and practical interest.

The majority of the known investigations are devoted to the systems with the revolving disc and the flow, directed perpendicularly to the plane of disk rotation, which corresponds to reactors of vertical type. There were no articles devoted to a heat transfer case from the disk being in a flow of the gas, running under some unrestricted angle.

Examples of a possible layout of the plane of rotation of a disk against the main stream are shown in figure 1. Figure 1 shows the case of an axisymmetric orthogonal flow, which is a subject of the active research in different applications since the first operation of von Karman in 1921, is illustrated.

Movement of a flow parallel to the disk plane in combination with rotation of the latter (fig. 1, b) leads to the axisymmetric flow in volume. The fall of a stream under some angle of attack to the disk plane with finite thickness leads to the flow separation on frontal (concerning the direction of movement of a flow) disk edges with the subsequent merge and appearance of boundary of turbulence (fig. 1, b –c).

![Figure 1. The schematic image of the field of flow nearby the fixed disk at axisymmetrical configuration (a), parallel movement with flow separation (b) and the position of a disk at an angle to the direction of movement of the main flow (c).](image)

In such a way, the common decision for a heteroaxial field of the flow colliding under some impinging angle with the cylinder with the finite radius revolving around its axis symmetries is unknown up to date. Namely this case needs to be considered in case of a research of the horizontal
reactor with the rotary substrate holder. Already in the first operations devoted to an in-depth study of the air flows over the rotating disk moving parallel to its plane, it was recognized that the strongest influence on behavior of a flow and processes of heat-transfer operations in the system effected the flow separation on the ring of a thick disk [5].

Also, along with rotational and progressive Reynolds numbers, the third important parameter in the description of the researched system is the angle of attack $\beta$ of a gas flow concerning the plane of a heated substrate holder. The fourth parameter is the ratio of thickness and radius of the cylinder – the part of a substrate holder appearing in the camera of the reactor which also influences the behavior of a flow: defines conditions of origin of separation of a flow and the layout of the boundary of turbulence.

In scientific works [3, 4], the results of detailed researches of the system with a thick plate in a parallel flow of gas are presented. In these works, the flow is generally characterized by the line of separation on a front edge of a disk and by the area of reattachment of a turbulent layer boundary (fig. 2).

A separation "bubble" in the median plane has a sweep of about 4-5 thicknesses of the substrate holder. These results correlate fully to the results of the research of the system with a plate in a flow. The field length of a flow reattachment becomes almost constant in cases when the Reynolds number, depending on the thickness of the plate and supply velocity exceeds 700 [6].

Figure 2. The image of the flow over a disk of the finite thickness with flow separation and reattachment.

The average heat transmission from the thick plate or disk is rather high that is explained by the existence of a turbulent barrier layer and the strong fluctuations of speed in the neighborhood of a separating "bubble" and a flow reattachment point. Taking into consideration these circumstances, it is possible to explain the maximum value of the average heat transmission in case $\beta=0^\circ$ that was observed in pilot researches [5, 7].

On the assumption of engineering aspects of the reactor block of installation of vapor-phase epitaxy of horizontal type for process optimization of epitaxy, it is necessary to research heat-transfer operations and movement of a flow of the carrier gas for a case of the rotating disk.

Investigational studies confirmed that nonuniformity in the distribution of a gas flow, emergence of separation points and flow reattachment, separating “bubbles”, turbulences, etc. leads to the emergence of a difficult heating pattern on a substrate surface even in case of an ideal construction of the heating system. This influence is defined by the angle of attack of a gas flow concerning a susceptor, the inflow speed of gas, the chamber pressure of the reactor, the adjustable change of speed of outflow of gas, the character of a current of gas drainage and a level of its heating at the input in the reactor [8-9].

6. Results obtained in experimental studies of nonuniformity of thermal field on surface of susceptor
In figure 4 there are results of the experimental studies of nonuniformity of thermal field on the surface of the revolving susceptor (diameter is 15.7 cm). The substrate holder (graphite M12) had one socket for a substrate with a diameter of 10 cm. In the figure, there is a change of temperature on the diametric line of movement of a gas flow along the surface of the susceptor to its center. The deviation from the preset value of the temperature making 1150°C was in the range from 1145 to 1154°C, i.e. – 5...+4°C.

Figure 3. Nonuniformity in the distribution of temperature on a substrate (in the examined case should not exceed 1°C).

The distribution of temperatures of the susceptor for the temperature of 1115°C after 90 minutes of growth of GaN-structures is given in figure 4. In this case, the disk from high-quality graphite (M16) manufactured in Japan was researched. The diameter of the substrate holder is 15.7 cm. This disk had 3 sockets under two-inch substrates.

Figure 4. Nonuniformity in the distribution of a temperature on a substrate of high-quality graphite.

7. Conclusion
Studies showed that nonuniformity of distribution of temperatures on the surface of the rotating substrate holder in MOVPE units amounts in average to +/− 5°C that is a very essential shortcoming.
Besides, in the majority of installations, owing to the non-optimal mode of a flow of the bearing gas, consequences of nonuniform growth of epitaxial structures on substrates were observed, which is related to existence of flow vortexes of gas and separating bubbles.

The authors suggest using the research results in the arrangement of the process of the increase in efficiency of the specified reactors that will allow increasing quality of the grown structures and reducing time of their growth.

8. Reference
[1] Pfennig Ch, Richter E, Weyers M and Trankle G 2008 Journal of Crystal Growth 310 911-915
[2] Beaumont B, Gibart P, Faurie J P 1995 Journal of Crystal Growth 156 140-146
[3] Sato H, Takahashi H, Watanabe A, Ota H 1996 Appl. Phys. Lett. 68 3617-3619
[4] Chtkchekine D G, Fu L P, Gilliland G D, Chen Y, Ralph S E, Bajaj K K, Bu Y, Lin M C, Bacalzo F T, Stock S R, 1997 J. Appl. Phys 81 2197-2207
[5] Neumayer D A, Cowley A H, Decken A, Jones R A, Lakhotia V, Ekerdt J G 1995 J. Am. Chem. Soc 117 5893-5894
[6] Zhilenkov A A, Efremov A A 2017 IOP Conference Series: Earth and Environmental Science 50 1-7
[7] Zhilenkov A A, Efremov A A 2017 IOP Conference Series: Materials Science and Engineering 177 1-5
[8] Chernyi S, Zhilenkov A 2015 Transport and Telecommunication Journal 16(1) 73-82
[9] Nyrkov A, Chernyi S, Zhilenkov A, Sokolov S 2016 DAAAM Proceedings 0672-0677 DOI: 10.2507/26th.daaam.proceedings.091