Conference Paper

Study of Microrelief Influence on Optical Output Coefficient of GaN-based LED

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Abstract

This work is devoted to the investigation of the influence on the light output coefficient of antireflective coatings by different configurations of the micro-relief formed on the light output surface of a GaN-based LED. The technology of the micro-relief fabrication in SiO_2-based antireflective coatings was developed with the use of electron-beam lithography (EBL) and contact photolithography. Simulation of the influence of the micro-relief of various proportions and configurations on the optical output coefficient was implemented. It was discovered that the micro-relief made with electron-beam lithography and contact photolithography increased the optical output coefficient.

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1. Introduction

One of the primary goals in the research of semiconductor light-emitting diodes based on gallium nitride and its solid solutions is to increase the external quantum efficiency of the light-emitting diode. There are several approaches to improving the extraction of light emitted from the semiconductor material into the surrounding media. It was discovered that combination of semiconductor wafer and transparent substrate by bonding technology can increase the light extraction [1] with the use of sophisticated geometries [2]. Another approach to enhance the light extraction is the surface roughening by wet etching process [3].

The external quantum efficiency SiO_2 of a light-emitting diode crystal is defined by two key parameters: internal quantum efficiency η_{int} and optical output coefficient h_{extract} :

$$\eta_{\text{ext}} = \eta_{int} \cdot h_{\text{extract}}. \quad (1)$$

The effect of total internal reflection, consisting in localization of the light inside the structure of a light-emitting diode, reduces the probability of the escape of photons from a semiconductor. Therefore, a coefficient of optical output of radiation is introduced, defined as the relation of the number of the photons radiated by a light-emitting diode to the number of the photons formed in the active area in a unit of time [4]. The optical output coefficient can be estimated as follows:

$$h_{\text{extract}} = \frac{P/(h\nu)}{P_{int}/(h\nu)}, \tag{2}$$

where P–power of the optical radiation escaping from a light-emitting diode; P_{int}–power of the optical radiation from the active area; and $h\nu$–energy of a photon.

Thus, the effect of total internal reflection on the border of a material with a high optical density (semiconductor) and a material with a low optical density (a sapphire substrate or air) is the key factor limiting the efficiency of the output of light. For the light-emitting diode crystals based on InGaN/GaN-heterostructures, the critical angle is $\sim 23^{\circ}$ (the refractive indexes of GaN and sapphire are 2.5 and 1.6). Thus, only a small part of the falling of photons on the section border at an angle within the range of $0 \ldots 23^{\circ}$ can leave a crystal.

An increase of the external quantum efficiency is possible due to the creation of light-dispersing surfaces and use of the antireflective coatings.

The aim of the work is the development of a technology for formation of a micro-relief in the antireflective coatings and simulation of the optical output coefficient.

2. Materials and Methods

2.1. Technology for formation of a micro-relief by means of electron-beam lithography

The formation of micro-relief surfaces in the antireflective coatings was developed on the example of SiO_2 films with the use of electron-beam lithography and contact photolithography.

For the creation of a micro-relief by means of electron-beam lithography, an SiO_2 film with a thickness of $80\ nm$ was deposited on a semi-conductor substrate by means of plasma-chemical deposition (PCD). A resistive mask was formed in the layer of the PMMA 950 positive resist. Exposure and combination were carried out on a Raith 150^{two} electronic lithographer with an accelerating voltage of $30\,kV$ and exposure dose of $450\ \mu mC/cm^2$. The exposed areas of the resist were developed in a mix of organic solvents of methyl isobutyl ketone and isopropyl alcohol. The time of development was determined by the quality of the windows opened in the resist.

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Through a resistive mask with a diameter of its windows of $0.5\,\mu m$ and distance between them of $0.5\,\mu m$, an isotropic etching of the SiO_2 layer was done. The image control in SiO_2 was carried out by means of a Raith 150^{two} electronic microscope. The image of the micro-relief was defined by the etching time. Figure 1 presents an image of the micro-relief received in the SiO_2 layer by electron-beam lithography.

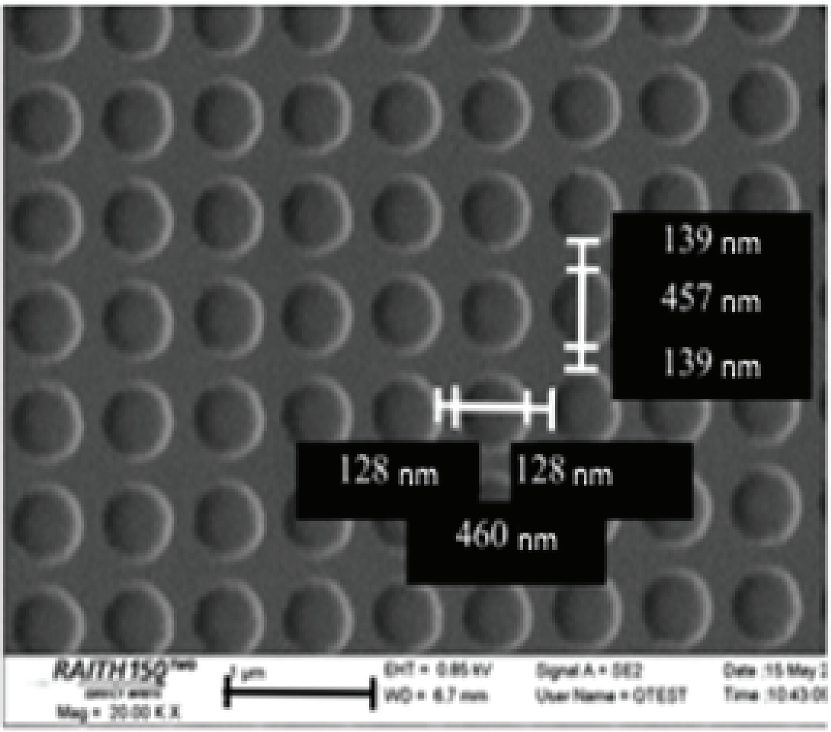

Figure 1: Image of the micro-relief received in layer by the method of electron-beam lithography (the time of etching of the sample was $40\ s$).

From Figure 1, it is visible that after etching for a duration of $40\ s$, a regular structure appears in the form of a round aperture in the SiO_2 layer with a depth of$70\ nm$, diameter of $460\ nm$ and a distance of 130 *nm* between them. The density of the apertures was $2.8 \cdot 10^8\ pieces/cm^2$. Between the deepenings in the SiO_2, a layer of a micro-relief was formed in the form of pyramids, located on a continuous layer of SiO_2 with thickness of $10\ nm$. If the etching time was increased up to$85\ s$, a micro-relief was formed in the SiO_2 layer in the form of microedges with regular structure. Thus, during the electron-beam lithography, due to the change of the time of etching of SiO_2 layer, it became possible to control the configuration of the micro-relief.

3. Formation of Micro-relief By Contact Photolithography

For formation of the microedges by the direct and reverse ('explosive') contact photolithography, a two-layer mask based on ERP-40–FP-051Shu-0.5 resists was used. Exposure was done through a photomask with aperture diameters of $1.31\ \mu m$ and with a distance between the windows of $1.43\ \mu m$. Due to the reverse lithography in the SiO_2 layer, microedges were obtained in the form of truncated trapeziums with a height of $439\ nm$, the size of the top base of $1.384\ \mu m$, and the bottom base of $1.83\ \mu m$ (Figure 2). The density of the edges was equal to $2.5 \cdot 10^7\ pieces/Am^2$.

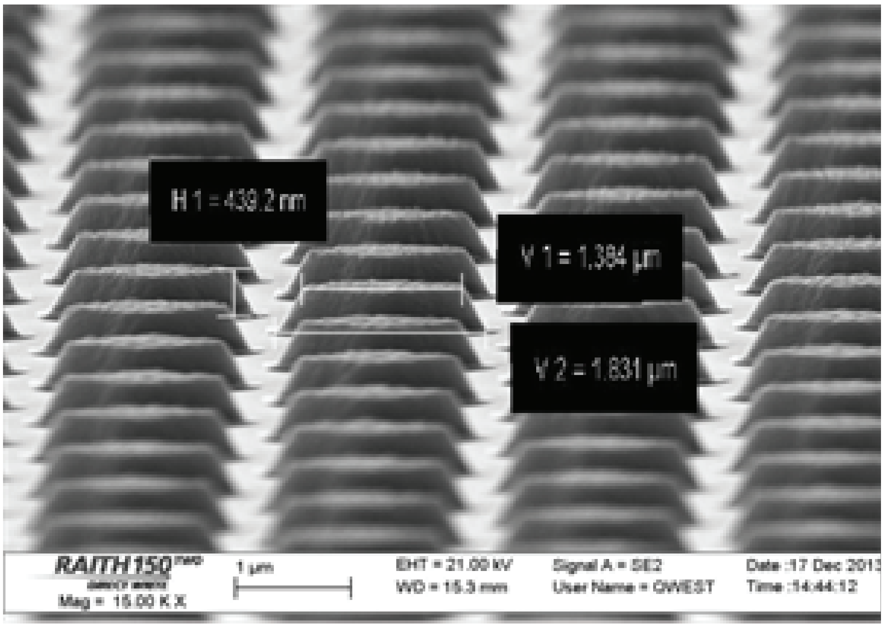

Figure 2: Image of the microrelief received in the SiO_2 layer by the method of reverse photolithography.

The micro-relief obtained by the direct photolithography was a set of ordered microedges locally connected between themselves in the remaining SiO_2 layer. The height of the points was $439\ nm$, the distance between them was $1.5\ \mu m$, and the diameter of the bottom basis was $0.43\ \mu m$. The density of the points was $1.6 \cdot 10^8\ pieces/cm^2$.

4. Results of Modeling of Optical Output Coefficient

For the research of the influence of a micro-relief surface on the optical output coefficient, simulation was done by means of NEMO LED software developed in the Chair of Physical Electronics of Tomsk State University of Control Systems and Radio-electronics. The given product allows us to model the propagation of a light beam in the multilayered structures with different refraction indexes of the layers and to investigate the influence of the micro-relief antireflective coatings on the relative number of the quanta of light, which escaped from the crystal (optical output coefficient).

For the research of the influence of the micro-relief in the antireflective coatings from SiO_2 and ITO with optical thickness of $\lambda/2$ in NEMO LED software, a model was developed, in which the lateral and bottom faces of the crystal of gallium nitride (refraction index $n_{\text{GaN}} = 2.5$) were covered by a reflecting material. On the top light-extracting face on the crystal side, a thin film was deposited with a refraction index smaller than that of gallium nitride ($n_{\text{SiO}_2} = 1.43$, $n_{ITO} = 1.9$), and a micro-relief of various configurations was formed in it (Figure 3). Radiation in the structure arose in the layer of gallium nitride.

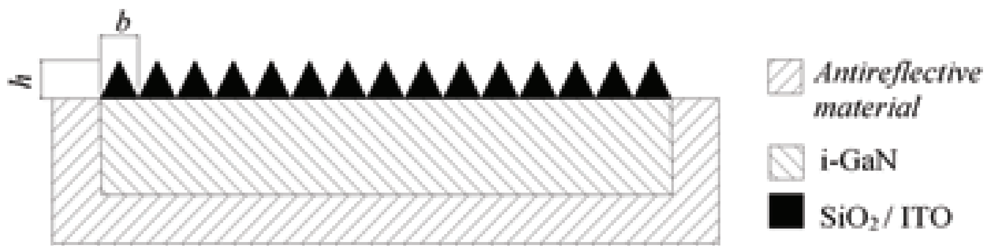

Figure 3: Image of the micro-relief received in SiO_2 layer, received by the method of reverse photolithography.

The given model allows us to investigate the efficiency of the output of light from the top face because it considers the quanta, which has no reflection during the passage of the border between the active area and the light-extracting layer (GaN). By defining the relative number of the quanta, which left the top face at various configurations of the micro-relief surface, it is possible to estimate the influence of a micro-relief on the coefficient of optical output of a light-emitting diode.

5. Discussion

Analysis of the received results shows that for a structure without an antireflective coating, the optical output coefficient is $h_{\text{extract}} = 0.37$. Hence, the crystal was left with 37 % of the photons, which came into the light-extracting layer of GaN from the active area. Deposition of the antireflective coatings increased this coefficient: for SiO_2 film, we received $h_{\text{extract}} = 0.41$, and for ITO film – $h_{\text{extract}} = 0.43$.

Formation of a micro-relief surface in an antireflective coating from SiO_2 in the form of pyramids, obtained by electron-beam lithography, resulted in an increase of the optical output coefficient up to $h_{\text{extract}} = 0.44$. Similar results were received for a micro-relief formed by reverse contact photolithography.

It was established that reduction of the distance between the pyramids resulted in the further increase of the number of the quanta of light, which escaped from the crystal, with preservation of the correlation of the sizes of the bottom basis of a pyramid to the top one of 3:1, which corresponds to the angle at the basis – $56.3°$.

During simulation of a micro-relief in the form of microedges, the correlation between the width and height of the microedge b/h changed, as did the distance between the points. It was established that the greatest optical output coefficient was in the structures with a micro-relief surface, where the basis of the edge was commensurable with its height, and the micro-relief elements were located densely to each other (Figure 4).

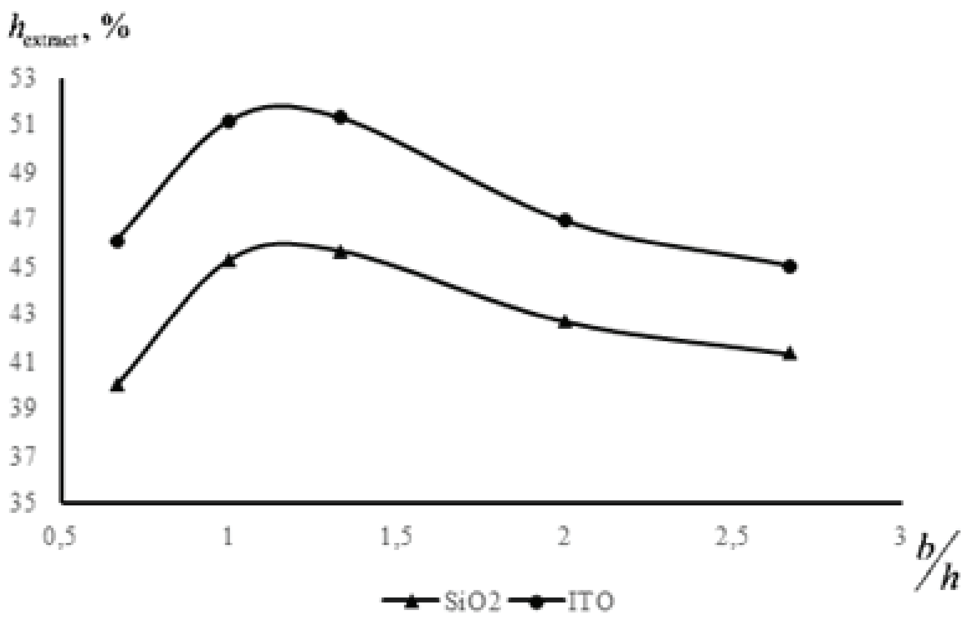

Figure 4: Dependence of the optical output coefficient on the width/height correlation of a microedge.

For the structures with the correlation of $b/h = 4/3$, the maximal value of the optical output coefficient was received: $h_{\text{extract}} \approx 51$ % for the ITO antireflective coating and $h_{\text{extract}} \approx 45.6$ % for the SiO_2 film.

6. Conclusion

It was established that the presence of the antireflective coatings and formation of a micro-relief in them increases the optical output coefficient. The technologies developed for the formation of a micro-relief in the antireflective coatings allow us to ensure a regular structure with a high density of edges – $10^7 \ldots\ 10^8$ $pieces/cm^2$.

The greatest optical output coefficient can be reached at the demanded correlation of the geometrical sizes and configuration of the micro-relief, which ensures a micro-relief angle at the basis of about $50 \ldots 60^{\circ}$.

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