InGaN/GaN heterostructures with lateral confinement for light emitting diodes

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Abstract. InGaN/GaN nanorod structure for light emission diode fabricated by the reactive plasma etching through the self-assembled Ni nano-cluster mask is presented. Fabricated array structure, presented in the form of truncated cones with average diameter height and period of nanorods is 250±50 nm, 430nm and 650±50 nm, respectively. The side angle of single structure about 80^o. EL spectrum has maximum at 460 nm.

1. Introduction
Fabrication of high-efficient optoelectronic devices (LEDs, PDs, lasers) is the key to the development of modern nanoelectronics. Further way of increasing efficiency is connected with using 3-dimentional structures, such as nanorods (NRs) and nanowire [1]. The formation of lateral confinement allows to decrease the transportation of the carriers in the dimension of the layers of heterostructures (to defects) and also to concentrate current in the light generating area where is performed (quantum dots). Furthermore, nanowires and NRs have practically non-defective structures [2]. One of the problems that can be solved with nanowires is increasing the light extraction efficiency from the structure by formation of effective resonator [3, 4]. With increasing of the efficient area, heating removing is also increased. There are different ways to fabricate such structures: catalytic and non-catalytic growth [5], growth with using electron-beam lithography [6]. Judging by technological process the easiest way to transfer to mass production is the technology of plasma chemical etching of planar LED structures with Ni nano-particles mask [7-9]. The aim of this study is development the technology of fabrication and investigation of properties of InGaN/GaN heterostructures with lateral confinement.

2. Experimental
The lateral confinement structure is fabricated using reactive plasma etching of planar LED heterostructures through the self-assembled Ni nano-cluster mask. In the work we use planar QD heterostructures (p-GaN/InGaN QD/n-GaN) grown by MOCVD on a-sapphire substrate. Ni mask is

formed by a deposition of ultrathin Ni film (about 5 nm) on the planar InGaN QD/GaN LED samples and followed by rapid thermal annealing (RTA). The samples through the self-assembled Ni nano-cluster mask are etched using ICP-DEP in gas mixture Cl_2 (20sccm) and BCl_3 (10sccm). Afterwards, the residual Ni nanoclusters is removed in solution of HCl:HNO_3 3:1. The contact formation is realized by polymer (SU-8) and ITO coating.
The surface morphology is studied using electron microscopy (SEM).

3. Results and discussions

3.1. Formation of Ni nano-masks

Preliminary, we investigated the formation of nanoparticles of Ni on Si(111) surface. Figure 1(a) shows SEM image of sample with a thickness of Ni layer: 2 nm, at the temperature of 850ºC and annealing time of 120 sec. The size distributions of Ni particles on the sample are given on the figure 1(b). Optimal RTA temperature of 850ºC is found for Ni nanoparticle (NP) formation.

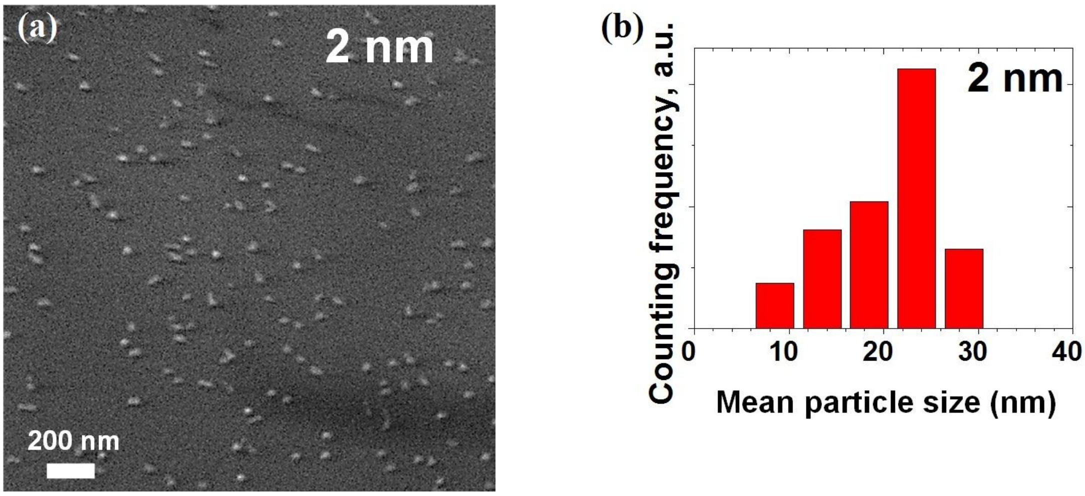


Figure 1(a, b). (a) SEM image of Ni particles on the Si(111) surface after annealing of Ni films thickness 5 nm, at 850ºC and 120 sec; **(b)** Size distributions of Ni.

When increasing the temperature of annealing to 900ºC the evaporation of the film is possible. With lower temperature the fabrication of particles is not noticed. During investigation this effect of the annealing time, we observe of increasing size particles by diffusion atomic and Osvald process [10]. On sample with efficient thickness of film 5 nm, we saw displacement islands as a result of the Brown's motion of the island as a whole. As time of annealing was increased, the density of the islands decreased and their series increased. Figure 2 shows that averaged size of Ni particles and their density dependent on the thickness of film by the matter conservation law in the system. The studying of Ni nano-mask formation on GaN based heterostructures (figure 3) demonstrates results near for Ni on Si. Notice the Ni islands have a hexagonal shape that is likely result from the crystal structure of the substrate.

3.2. Formation of nanorod structure

The average diameter of the NRs is ranging from 250±50 nm, height of the rod is about 430nm and the period is about 650±50 nm. Different etching angles (77±2^{o} and 80±2^{o} for p- and n-GaN layer, respectively) show clearly the active layer position in the structure (figure 4). Most probably, every nanorod acquired at least one quantum dot.

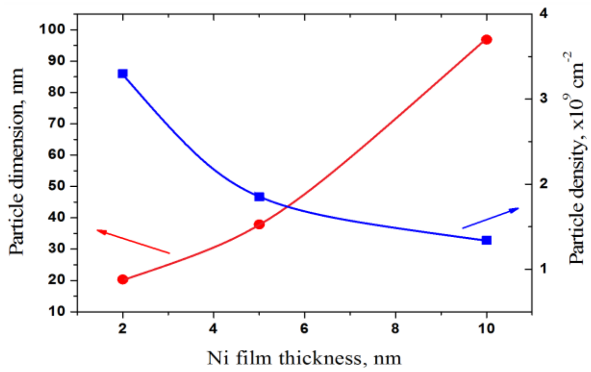


Figure 2. Average size and density of the Ni particles as a function of the initial Ni thickness for RTA at 850◦C, 120 sec.

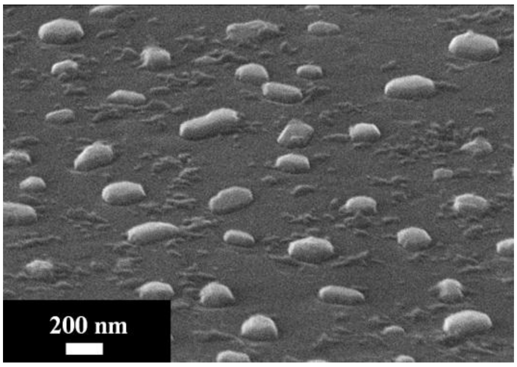
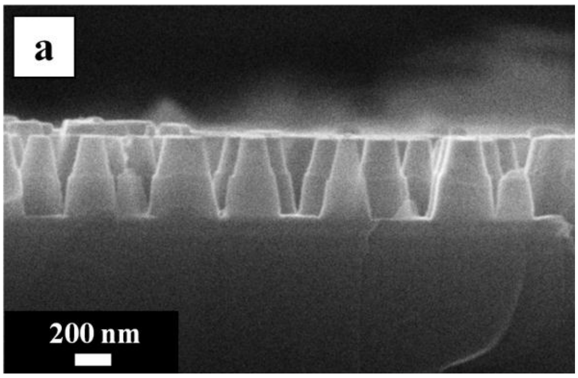


Figure 3. Ni particles on GaN surface fabricated by 5 nm Ni film deposition and RTA at 850◦C, 120 sec.



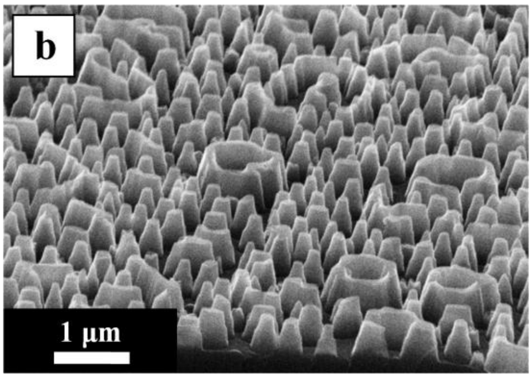


Figure 4(a, b). Cross section **(a)** and isometric **(b)** view of the GaN sample after ICP etching.

3.3. Optoelectronic properties

Figure 5(a) shows PL intensity of the NR structure with measured at temperatures of 10 K and 300 K (blue and black lines, respectively) comparing to planar one at room temperature (green line). The short wavelength peak can be described by the luminescence of the bulk GaN layer. The peak shifts expectedly to the longer wavelengths with rising of the temperature. Long-wavelength peak describes optical answer of the InGaN active layer and leads himself in a more complex manner. The peak hasn't red-shift nature and increasing of spectral width. Such behavior can be explained by indium surface segregation (ISS) effect. After the formation of NR, these islands can act as separated quantum dots with superior enhancing of the optical gain properties and temperature stability. Increasing of the indium content decreases band gap energy, while quantum dots naturally spread energy [11]. Both effects compensate each other and keep wavelength stable. While the PL intensity of the single quantum dot is naturally very narrow, we can suggest that the broad width of our NRS spectrum at low temperature causing by the total sum of different quantum dots [12] and random values of NR diameters. In addition, it is well known that there exists strong strain-induced piezoelectric fields exerted across InGaN/ GaN MQWs, causing a quantum confined Stark effect (QCSE) [13] and thus generating a red shift in emission peak. The optical pumping induced blue shift in emission peak, which occurs to our InGaN/GaN NRS structure, confirms that the strain has been relaxed. The peaks of the spectra are between 450-470 nm. Presented on figure 5(b) electroluminescence (EL) spectrum has similar peak in the same area. Light extracted from NR structure is shown in the inset of figure 5(b). One of the problems during etching is the evenness of the height of NR that decreases the light extraction efficiency. *VI* characteristic of the fabricated nanorod LED shows 2.2 V of the cutoff voltage.

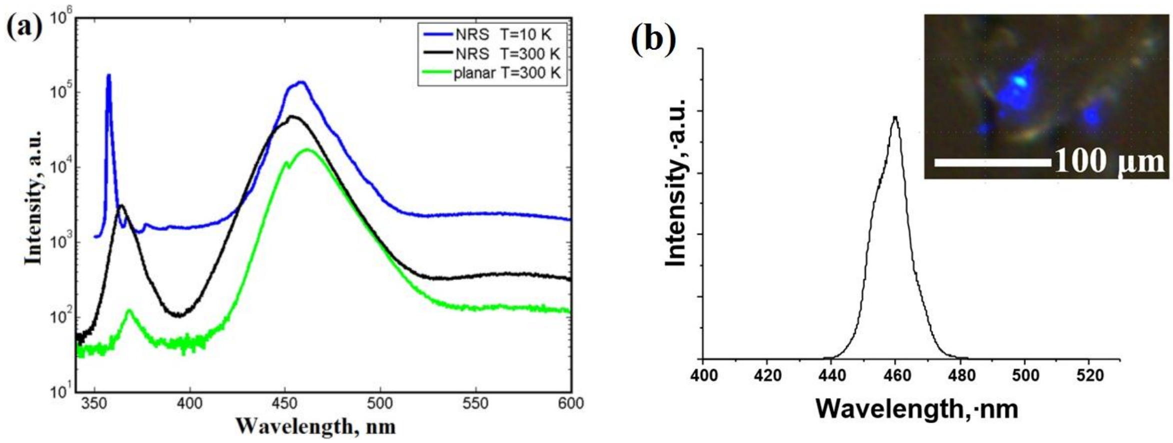


Figure 5(a, b). **(a)** PL spectra of initial and nanorod structures; **(b)** EL spectrum nanorod structures.

4. Conclusion

Lateral confined InGaN/GaN heterostructures were fabricated. We investigated the main processes of the formation of Ni – mask. PL intensity behaviour shows high temperature stability over a wide range of temperatures. The peak of improved structure showed 2.8 times enhancement and 9nm (54meV) blue-shifting comparing to the planar one at room temperature. After the nanorod formation, quantum dots, formed by the indium surface segregation, can act as separated quantum dots with superior enhancing of the optical gain properties and temperature stability. Optoelectronic properties of the nanorod LEDs were demonstrated in the range of 450-470 nm.

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