InGaN nano-LEDs for energy saving optoelectronics

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Vertically integrated III-nitride nano-LEDs designed for operation in the telecommunication-wavelength range were fabricated and tested in the (p-GaN/InGaN/n-GaN/sapphire) material system. We found that the band edge luminescence energy of the nano-LEDs could be engineered by their size and by the strain interaction with the masked SiO_2/GaN substrates; it depends linearly on the structure size. The results of reliability measurements prove that our technological process is perfectly suited for long-term operation of the LEDs without any indication of degradation effects. The presented technology shows strong potential for future low energy consumption optoelectronics.

1. Introduction

Single photon emitters based on InGaN nano-LEDs (light emitting diodes) operating at room temperature are the key to enable future low energy consumption, highly secure and ultrafast optoelectronics [1]. There is an especially strong need to develop such emitting sources at the wavelengths used for telecommunication, which are fully compatible with established communication systems. Major challenges are the whole nano-LED integration technology and especially the contacts. The top contact should be highly electrically conductive, highly optically transparent, thermally and mechanically stable and simple to fabricate.

2. Device fabrication

First, we started with the site-controlled growth of InGaN nanostructures via catalyst-free selective-area MOVPE [2]. The manufacturing process was optimized with respect to the mask pattern in order to be able to fabricate individually addressable InGaN nanopyramid based nano-LEDs. The starting point for growth were uniform and smooth n-GaN layers of at least 1.3µm on sapphire (c-plane) masked with SiO_2. Afterwards a hexagonally arranged array of openings was defined by electron beam lithography followed by reactive ion etching (RIE) with trifluoromethane (CHF_3) gas. The separation distance was fixed to 3µm and the bottom hole diameter was varied from 20 nm to 100 nm. All samples were grown by MOVPE in an AIX 200/4 RF-S horizontal flow reactor (AIXTRON). The growth parameters were tuned with respect to the highest possible selectivity. After this optimization, the growth time was

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varied in order to study the evolution of nanostructures with respect to their morphology and their optical properties [3].

Afterwards, the InGaN nanopyramids were integrated into a device layout for DC testing and future high-frequency operation. The fabrication process is described in figure 1. After mesa isolation, bottom contacts were defined by optical lithography and, subsequently, Ar-ion beam etching (IBE) was used to remove the SiO_2 layer (figure 1b). This technology is sensitive to etching parameters to minimize surface roughening / damage and to reduce detrimental in-depth defects due to channelling. In the next step – after metallization with Ti/Al/Ni/Au – bottom contacts (figure 1c) were annealed in nitrogen ambient under optimized temperature to prevent InGaN nanopyramid degradation. Thereafter, transparent top contacts (Ni/Au or conductive polymer) were deposited on top of the p-GaN/InGaN nanopyramids (figure 1e) and subsequently handled with an optimized thermal annealing process. Additionally the entire surrounding surface area (except for the mesa with bottom and top contacts) was coated with a 200 nm SiO_2 layer to prevent leakage currents. In the last step, the InGaN nanopyramid based nano-LED device was connected to contact pads (Ti/Au) for DC testing and future RF operation by employing optical lithography and a lift-off process (figure 1f).

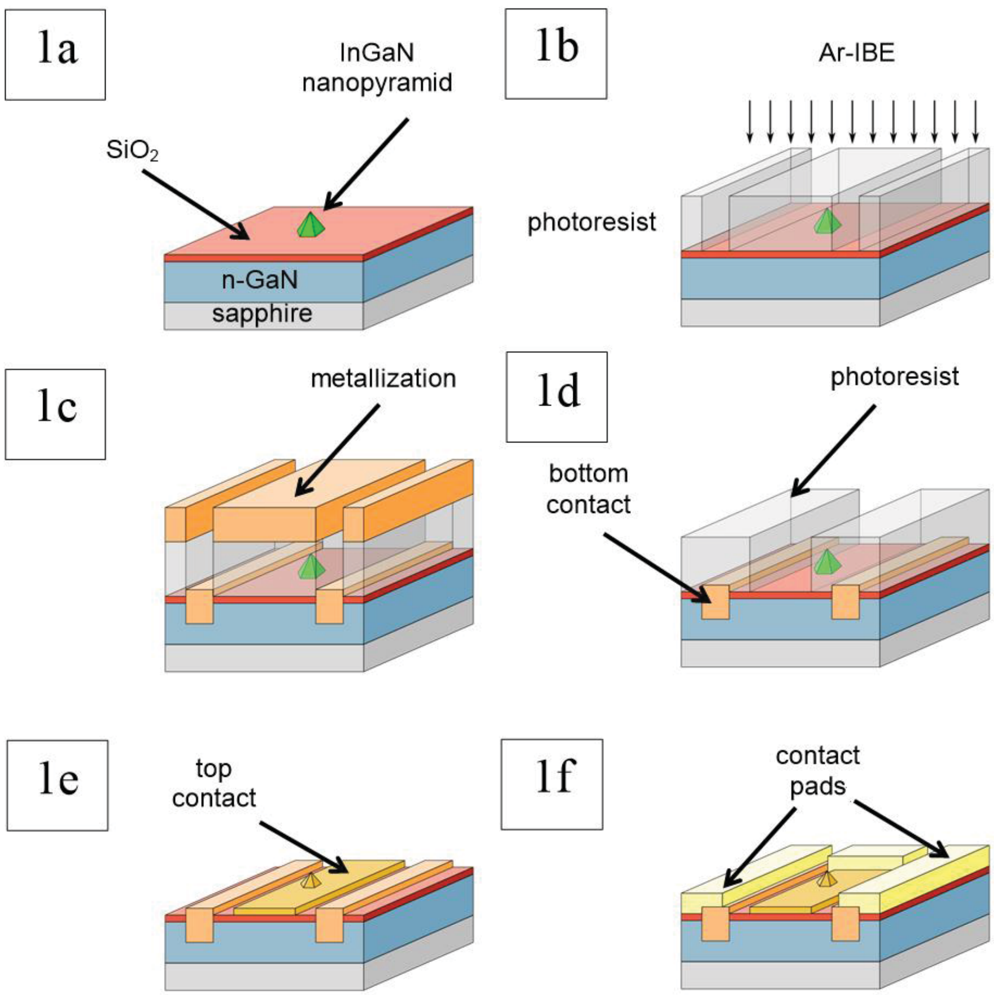

Figure 1: Integration of III-nitride based nano-LED structure into a vertical device layout.

In figure 2 SEM micrographs are presented of the prototype nano-LED device described above at different magnifications.

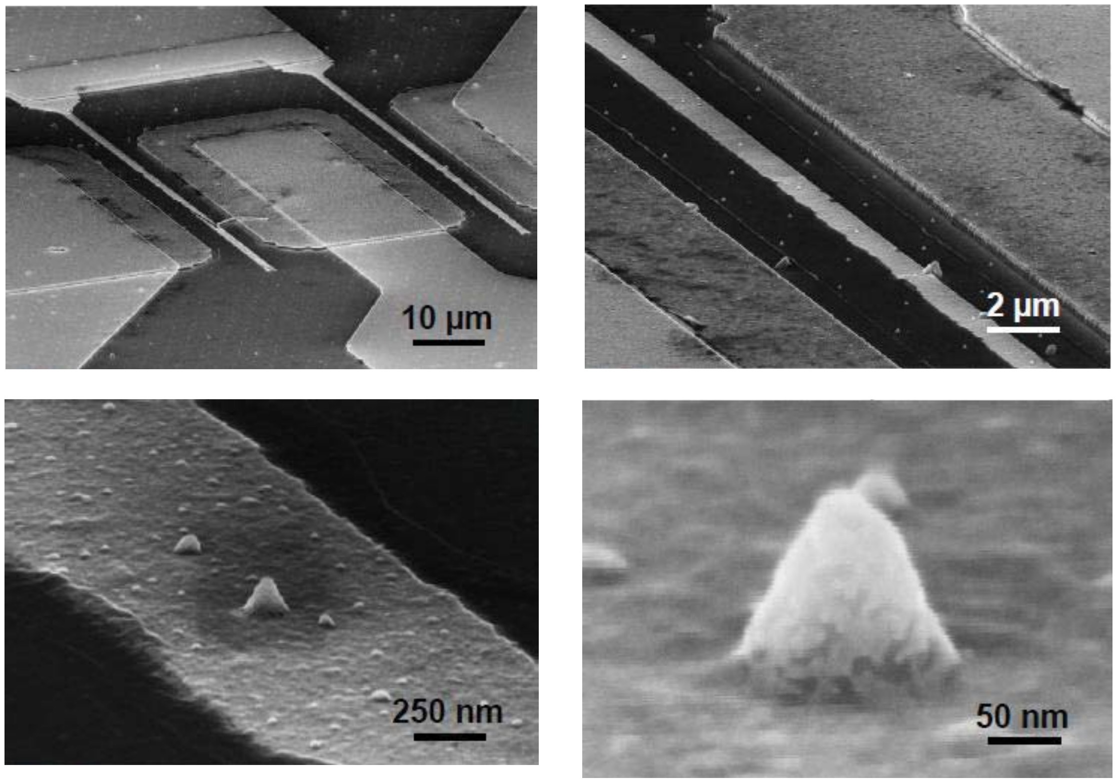

Figure 2: Scanning electron micrographs (SEM) with different magnifications for the integrated InGaN nanopyramid in a device layout for DC and RF operation.

3. Micro electroluminescence and DC characterization

Micro electroluminescence (EL) measurements were used to characterize the nano-LEDs (figure 3a). All devices show the same range of EL intensity. In addition, nano-LEDs were tested in a quasi operation mode at 4 V bias for 1000 hours (figure 3b). The intensity decreases only moderately with time - somewhat earlier for the smaller than for the larger device and exhibits long-term stability for the larger device after about 10 hours of operation. The intensity decrease - similar to the moderate increase in dark currents disclosed in figure 4b - is attributed to current heating effects. We found that the band edge luminescence energy of the nano-LEDs as well as their emission intensity depend linearly on their structure size (figure 4a). We explain the size dependence of the luminescence energy to different degrees of strain originating from the interaction of the nano-LED with the surrounding SiO_2 isolation mask. Strain can therefore be used to tune the wavelength emission of III-nitride nano-LEDs. The nano-LEDs were tested in DC measurements using a quasi-operation mode at 4V bias voltage for 1000 hours for selected top contact materials. The tests show no indications of degradation or current collapse and only a ~ 5% increase of dark current (figure 4b).

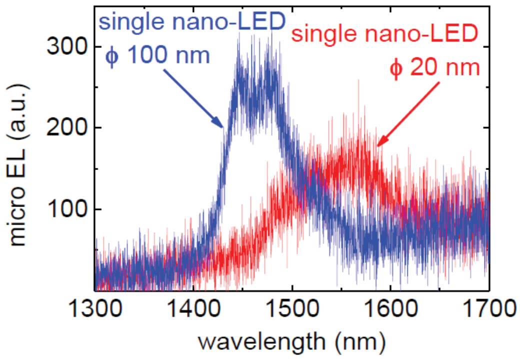

Figure 3a: Micro electroluminescence measurements for single 20 nm and 100 nm (diameter) vertically intergrated nano-LED structures.

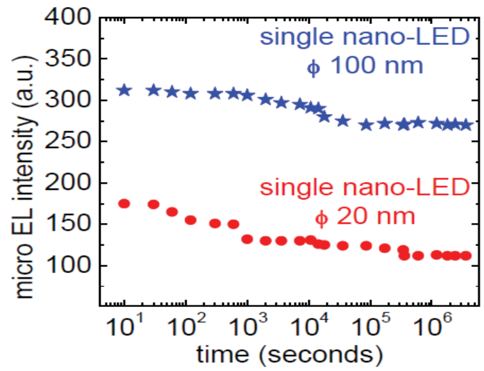

Figure 3b: Reliability measurements- micro EL intensity measured for 1000 hours at 4 V bias.

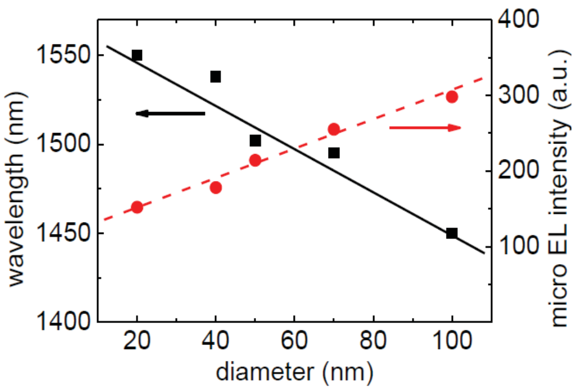

Figure 4a: Wavelength emission and micro EL intensity as a function of nano-LED diameter.

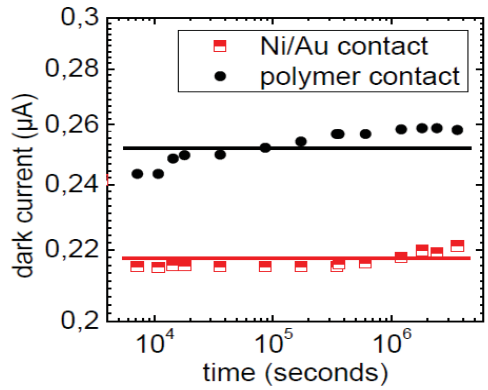

Figure 4b: Comparison of a Ni/Au and a polymer contacted nanopyramids tested in DC measurements using quasi operation mode under 5V reverse bias voltage for 1000 h.

4. Conclusion

A successful technological integration and material compatibility of selected metallic and polymer materials with InGaN nanopyramids was carried out [2]. A very low specific contact resistance below 6.9×10^{-6} Ωcm^2 was found for annealed standard Ni/Au contacts on the p-type GaN cap layer and a light transmittance of about 72% was measured at 1550 nm. A top contact created by a thin layer (~ 20nm) of p-dot conductive polymer showed a light transmittance even up to 89%. Our results demonstrate the potential of InGaN/GaN nanostructures for future low energy consumption and reliable nitride based emitting sources for the operation at the telecommunication wavelength range.

References

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