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Pinhole microLED Array as Point Source Illumination for Miniaturized Lensless Cell Monitoring Systems †

Shinta Mariana [1,*], Gregor Scholz [1], Feng Yu [1], Agus Budi Dharmawan [1,2], Iqbal Syamsu [1,3], Joan Daniel Prades [4], Andreas Waag [1] and Hutomo Suryo Wasisto [1,*]

1 Institute of Semiconductor Technology (IHT) and Laboratory for Emerging Nanometrology (LENA), Technische Universität Braunschweig, 38106 Braunschweig, Germany; gregor.scholz@tu-braunschweig.de (G.S.); f.yu@tu-braunschweig.de (F.Y.); a.dharmawan@tu-braunschweig.de (A.B.D.); i.syamsu@tu-braunschweig.de (I.S.); a.waag@tu-braunschweig.de (A.W.)
2 Faculty of Information Technology, Universitas Tarumanagara, 11440 Jakarta, Indonesia
3 Research Center for Electronics and Telecommunication, Indonesian Institute of Sciences (LIPI), 40135 Bandung, Indonesia
4 MIND, Department of Electronic and Biomedical Engineering, Universitat de Barcelona, 08028 Barcelona, Spain; dprades@el.ub.edu
* Correspondence: s.mariana@tu-braunschweig.de (S.M.); h.wasisto@tu-braunschweig.de (H.S.W.)
† Presented at the Eurosensors 2018 Conference, Graz, Austria, 9–12 September 2018.

Published: 21 November 2018

Abstract: Pinhole-shaped light-emitting diode (LED) arrays with dimension ranging from 100 µm down to 5 µm have been developed as point illumination sources. The proposed microLED arrays, which are based on gallium nitride (GaN) technology and emitting in the blue spectral region (λ = 465 nm), are integrated into a compact lensless holographic microscope for a non-invasive, label-free cell sensing and imaging. From the experimental results using single pinhole LEDs having a diameter of 90 µm, the reconstructed images display better resolution and enhanced image quality compared to those captured using a commercial surface-mount device (SMD)-based LED.

Keywords: microLED; pinhole; point light source; cell monitoring; compact lensless holographic microscope; microfabrication; cell imaging

1. Introduction

For evolving applications in life sciences (e.g., non-invasive, label-free cell counting and imaging), a compact system based on digital inline-holographic microscopy provides a lightweight and cost-effective platform, which can be integrated inside an incubator set-up enabling a real-time, in situ and continuous biological cell monitoring [1]. Although commercial SMD-packaged LEDs can be employed, they still have limitations in terms of size, integration flexibility, spatial illumination coherency and therefore achievable image resolution, especially when extension to 3D imaging and pixel super-resolution capabilities are required [2]. Combining SMD LEDs with optical fibers [3] or a separate metal pinhole and a piezo-stage [2] can offer quick alternative solutions for realizing an array of small, separately controllable light emitters. However, the efficient optical interconnections between those two elements, as well as device miniaturization still remain a challenge. Therefore, smaller coherent point light sources forming arrays, being specifically designed and fully integrated into a miniaturized imaging system, would offer tremendous advantages.

In this work, blue LED wafer based on InGaN/GaN multi quantum well (MQW) is used to realize pinhole-shaped microLED arrays with openings ranging from 100 µm down to 5 µm. After fabrication process, the resulting pinhole LED is characterized optoelectronically prior to integration into the miniaturized lensless microscope. The results of the cell imaging will also be compared.

2. Fabrication Method and Results

Pinhole LED arrays have been designed and fabricated from planar two-inch epitaxial GaN LED wafers (E-Wave Corporation, United Kingdom) using processing flow steps shown in Figure 1. Each wafer consists of several layers, including a 430 μm thick sapphire substrate, 3.36 μm thick *n*-GaN layer (Si-doped, ~1.5×10^{19} cm^{-3}), 0.4 μm thick InGaN/GaN MQW as active layer, and 0.3 μm thick *p*-GaN layer (doped with Mg in the range of ~8.9×10^{18} cm^{-3}).

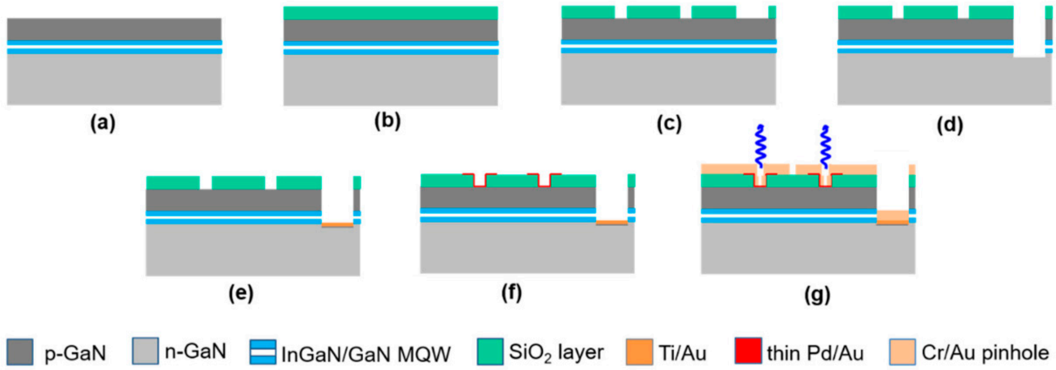

Figure 1. Fabrication process of pinhole LEDs, consisting of (**a**) preparation and cleaning of GaN-based LED sample with InGaN/GaN MQW, (**b**) deposition of SiO_2 as an insulating layer, (**c**) opening of holes and contact areas on SiO_2 layer, (**d**) dry etching down to *n*-GaN layer, (**e**) deposition of Ti/Au as *n*-contact, (**f**) deposition of thin and semitransparent Pd/Au as *p*-contact, (**g**) metallization of Cr/Au, subsequently defining pinhole openings, which emit blue light after contacting.

To start the fabrication of the device, an insulating 50 nm SiO_2 layer was deposited on the *p*-GaN surface of GaN LED wafer using plasma-enhanced chemical vapor deposition (PECVD) (Figure 1b). It was followed by sequential photolithography and etching process using buffered hydrofluoric acid to realize openings of the holes (for semitransparent *p*-contact) and larger *n*-contact areas on the SiO_2-layer (Figure 1c).

Openings at *n*-contact areas were etched down by using hybrid etching method [4] (Figure 1d), combining inductively coupled plasma dry reactive ion etching (ICP-DRIE) and potassium hydroxide (KOH)-based wet chemical etching. The depth of the etched structure can be easily controlled by adjusting the etching durations. To reach *n*-GaN layer, dry etching was performed for 12 min with controlled parameters [5], resulting in a trench depth of approximately 1.5 μm. Smooth *n*-GaN surface was highly required for better adhesion to the metal contact. Thus, two hours wet etching and a cleaning step using boiled mixture of H_2SO_4/H_2O_2 were carried out. Because of adhesion issues between GaN and gold layer [6], 10 nm thin titanium film, acting as an intermediate layer, was deposited before depositing 300 nm gold layer to form the *n*-contacts. Both depositions of metal layers were conducted using electron beam evaporation (Figure 1e). After sequential photolithography, a 3 nm and 10 nm thin semitransparent Pd/Au metal layer was deposited as *p*-contact (Figure 1f). Then, the *n*- and *p*-contacts were annealed at 600 °C for 30 s to ensure the formation of good Ohmic contacts.

In case of light coming out from other spots than the pinhole opening, the surroundings of the gold interconnections could be covered by a layer of photoresist to act as passivation layer and a non-transparent 200 nm Au to prevent the light leak. The wafer was then diced and bonded to a printed circuit board (PCB), enabling a free controllable LED array as point light sources (Figure 2a).

Prior to integration into the lensless holographic microscope, the LED device was characterized in electroluminescence (EL) measurements at room temperature. The measured I-V curves (Figure

2b) indicate that the LED device can be operated under normal bias voltages of ~3 V, proving the formation of a good Ohmic contact.

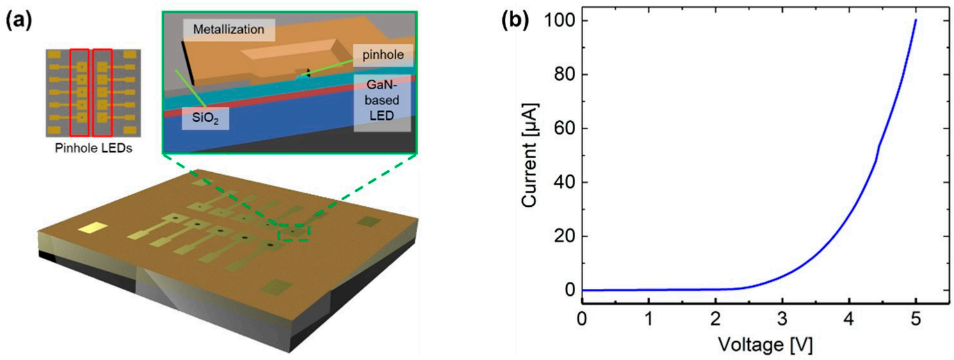

Figure 2. (**a**) Principle sketch of the pinhole LED arrays. (**b**) Measured I-V curve of a single pinhole LED having a diameter of 90 μm.

For testing the capability of the homebuilt pinhole LEDs as an enhanced point light source, a single 90 μm pinhole LED was assembled into a lensless holographic microscope to image polystyrene microbeads with diameters of 20 μm, 10 μm and 5 μm, which was embedded in transparent polydimethylsiloxane (PDMS). This size range is comparable to the size of most cells [7]. The images captured by the lensless microscope contain many diffraction patterns due to the large lateral coherence length of the μLED emission. A lot of information can be extracted from this interference patterns. After being processed in a reconstruction software using the angular spectrum method, a high resolution image can be achieved. Further image enhancement methods and artefact reductions can also be applied [1,2]. From the reconstructed images shown in Figure 3, we observed that the resolution of the reconstructed images was increasing with smaller μLED dimensions.

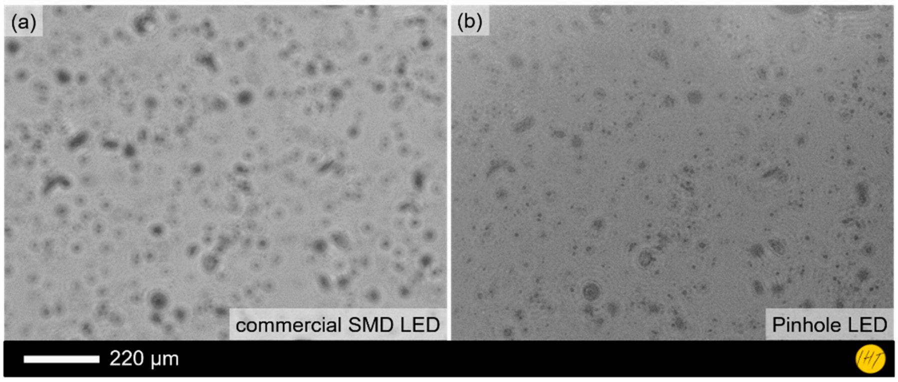

Figure 3. Side-by-side comparison of reconstructed inline-holographic images of 5 μm polystyrene microbeads embedded in transparent polydimethylsiloxane (PDMS) mold using illuminations of (**a**) a commercial blue SMD LED with a size of 230 × 230 μm^2 and (**b**) a single pinhole LED with diameter of 90 μm, both at a wavelength of 465 nm. In contrast to (**a**), clear diffraction patterns can be seen in (**b**) due to the larger spatial coherence length of the microLEDs.

Furthermore, the focus values of the images were calculated using modulation transform function (MTF), which differentiates various spatial frequencies or contrasts in the picture and defines "1" as the highest focus value [8]. The usage of pinhole LEDs improves the image focus value to 0.35, in comparison to the focus value of 0.17 obtained from the usage of commercial LED, confirming the better obtained image quality (i.e., higher focus produces clearer appearance of the image).

3. Conclusions and Outlook

Pinhole-shaped microLED arrays that have been fabricated from planar GaN LED wafer offer tremendous advantages compared to the other near coherent point light sources, such as commercial LEDs coupled with optical fibers or metal pinholes in piezo stage. The illumination coherency and integration flexibility as a point light source have been proven by combining the pinhole LEDs with a lensless holographic microscope, resulting in a better image quality for continuous and label-free cell monitoring that has been demonstrated quantitatively by twofold increase in image focus value. It is due to the fact that the reduction of the pinhole diameters can enhance the coherence of the light source, leading to a quality improvement of the obtained microscopy images. As the next step, fabrication of pinhole LEDs with diameter down to 500 nm will be strived for, even though the reliability of such nanoLEDs as point light sources should be investigated thoroughly in the near future.

Author Contributions: Conceptualization, H.S.W., G.S. and S.M.; Methodology, S.M. and G.S.; Software, G.S., I.S. and A.B.D.; Validation, S.M. and F.Y.; Formal Analysis, S.M., F.Y., G.S., H.S.W. and J.D.P.; Investigation, S.M.; Writing-Original Draft Preparation, S.M.; Writing-Review & Editing, all authors; Visualization, S.M. and G.S.; Supervision and Project Administration A.W. and H.S.W.; Funding Acquisition, J.D.P., A.W. and H.S.W.

Funding: This work has been partially performed within LENA-OptoSense funded by the Lower Saxony Ministry for Science and Culture (N-MWK) and European project of ChipScope funded by the European Union's Horizon 2020 research and innovation program under grant agreement No. 737089. S.M. thanks the Georg-Christoph-Lichtenberg Ph.D. scholarship (Tailored Light). F.Y. is grateful to the financial support from the China Scholarship Council (CSC) for the scholarship under the Grant CSC No. 201206010284. A.B.D. thanks Kemenristekdikti-LPDP for the Ph.D. scholarship. I.S. acknowledges the Ministry of Research, Technology and Higher Education (RISTEKDIKTI) for the Ph.D. scholarship of RISET-Pro. This work has been partially supported by the European Research Council, under the European Union's Seventh Framework Programme (FP/2007-2013)/ERC Grant Agreement No. 336917. J.D.P. acknowledges the support of the Serra Húnter Program and the DFG Project GrK NanoMet.

Acknowledgments: The authors thank A. Schmidt, J. Breitfelder, and M. Rühmann for their technical support during the experiments, as well as Institut für Mikrotechnik (IMT) for providing PECVD and metal pinhole. The support of I. B. Tanjung in modelling and PCB design is also highly appreciated.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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