**Paper 36-4** has been designated as a Distinguished Student Paper at Display Week 2025. The full-length version of this paper appears in a Special Section of the *Journal of the Society for Information Display (JSID)* devoted to Display Week 2025 Distinguished Papers. This Special Section will be freely accessible until December 31, 2025 via:

**https://sid.onlinelibrary.wiley.com/doi/full/10.1002/jsid.2069**

Authors that wish to refer to this work are advised to cite the full-length version by referring to its DOI:

**https://doi.org/10.1002/jsid.2069**

# Bottom-Emitting Striped MicroLED Array Light Source for Uniform Optical Sectioning Structured Illumination Microscopy

*Oliver Durnan*, Vikrant Kumar, Ikponmwosa Stephen Ogunmwonyi, Ioannis Kymissis*

**Dept. of Electrical Engineering, Columbia University, New York, NY, USA**

***Student Presenter, oliver.durnan@columbia.edu**

## Abstract

***This work demonstrates a microLED light source for optical sectioning structured illumination microscopy (OS-SIM). A bottom-emitting design is employed to improve the uniformity and intensity of emission by removing the anode contact from the optical path. This design facilitates the addition of a potential equalizing and light-reflecting layer to the top surface of the light source. The irradiance, uniformity of light emission, and contrast ratio are characterized.***

## Author Keywords

Structured illumination microscopy; Optical sectioning structured illumination microscopy; SIM; OS-SIM; Neural circuits; Neural tissue imaging; MicroLED microscopy; Fluorescence microscopy; Miniature microscopes.

## 1. Introduction

To gain insight into the working principles of the brain and to develop treatments for neurological disorders, it is necessary to study the physical structures within. These structures may be as large as millions of neurons, forming sophisticated neural circuits, serving complex processes such as regulating behavior and changing mental states. The functions governing these processes are believed to emerge from the simultaneous and dynamic interaction of the constituent neurons [1].

To optically investigate the behavior of these neural circuits, it is essential to be able to capture images covering the entire volume of the neural circuit. Additionally, high imaging frame rates are required to assess the transient behavior of the circuit. In light of this, developing large field of view, high speed, depth-sensitive, and high contrast microscopy tools is critical for studying neural circuits.

One technique to achieve high contrast ratio imaging while maintaining high spatial and temporal resolution is OS-SIM [2,3]. Using the OS-SIM technique, the sample to be imaged is illuminated by a light source whose intensity has a periodic modulation along one direction. After several images of the sample are captured with different phase offsets in the illumination pattern, a final image can be reconstructed which offers improved contrast in comparison to a single widefield image captured with illumination of similar intensity [4].

To generate these phase-modulated patterns, widefield light sources have typically been employed in tandem with spatial light modulators (SLMs) [4-6]. Recently however, microLEDs have emerged as a promising technology platform for creating OS-SIM illuminators due to their extreme luminance, high contrast ratio, and small emitter size [7]. Further, microLEDs offer the benefit of superior miniaturizability when compared to SLMs. Moreover, they can also improve the simplicity of the optical setup by combining the light source and light sectioning functions into a single element. Consequently, interest has grown in microLED light sources for OS-SIM and stripe-patterned individually addressable microLED arrays have been demonstrated in the literature for this purpose [8-10].

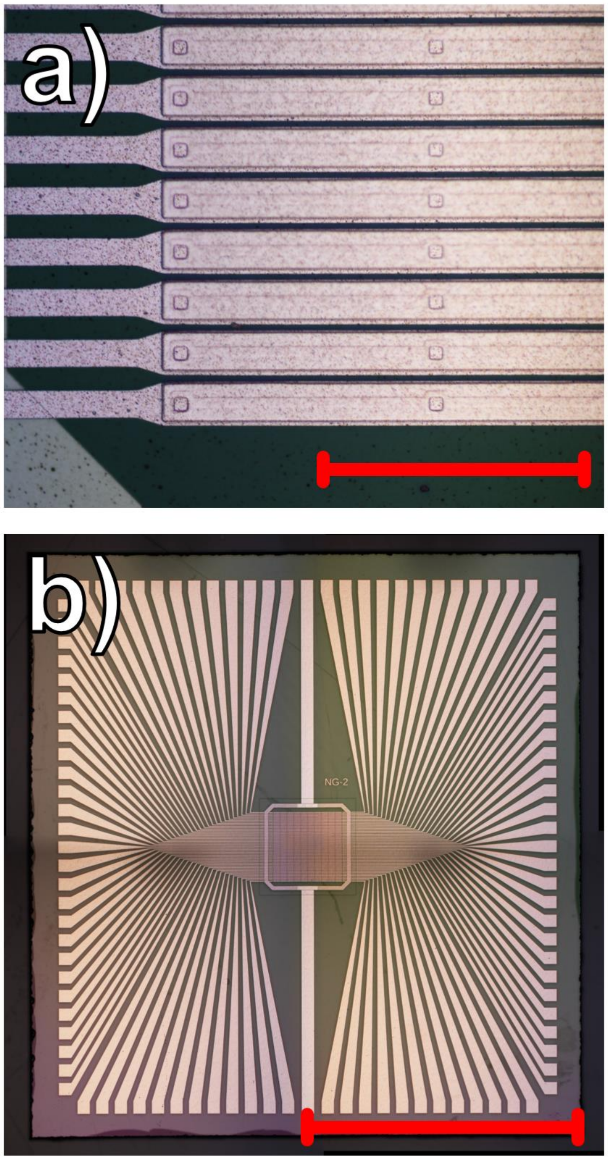

**Figure 1.** a) Image of the light source showing the individual stripe elements running horizontally – scale bar 100 µm. b) Image showing the overall layout of the light source chip, with the active area in the center and bond pads along the periphery – scale bar 4 mm.

## 2. Methodology

***Design:*** The general design goal for an OS-SIM light source is to create an individually addressable array of striped light-emitting elements. To improve the imaging quality, the light output intensity and fill factor of the elements of the light source should be maximized while the width of the elements is minimized to allow for the generation of fine patterns. Of course, there is a tradeoff between fill factor and emitter size and similarly, nonradiative sidewall recombination has been shown to reduce efficiency and thus irradiance as microLED emitters are scaled downwards in size [7]. Therefore, these parameters must be co-designed with their respective tradeoffs.

With this in mind, we designed an array of 51 bottom-emitting horizontal microLED stripe elements. Each stripe is 16 µm by 1016 µm with a center-to-center distance of 20 µm, leaving a 4 µm gap between any two adjacent stripes. This results in an areal fill factor of (1016/1016) • (16/20) = 80% for the active area of the array. Since studies suggest that sidewall recombination losses can be mitigated by strategic sizing and placement of anode contacts such that the distance between the contact edge and an etched microLED mesa sidewall is larger than the carrier diffusion length in GaN [11], we have designed Ni/Au anode contacts 3 µm in width which run the length of each stripe.

Since each anode contact is only 3 µm wide, but covers the entire 1016 µm length of each stripe, the resistance across the contact becomes significant due to the large aspect ratio. This leads to a resistive droop down the length of each stripe and consequently different biasing conditions being present at each position, resulting in non-uniform current density and light generation. To alleviate this problem, an additional low-resistance interconnect layer is used on the top of each stripe with vias periodically descending to connect it to the anode contact and equalize the potential at each point. Since this layer does not have to form an ohmic contact to p-type GaN, we are free to choose its material and thickness, and we select a 500 nm thick layer of Al for the purpose. Al is suitable for this layer for several reasons. Its low resistivity is advantageous because it allows for less voltage drop down the stripe. Secondly, its high reflectivity allows for the collection of stray top-emitted light. Instead of being lost out of the top of the device, it is reflected downward where it can be gathered by the downstream optics. Furthermore, each stripe has a dual-side drive scheme, and current is injected from each end to further reduce the length-dependent voltage drop. Figure 2 illustrates a cross-section of two stripe elements as well as a common cathode contact.

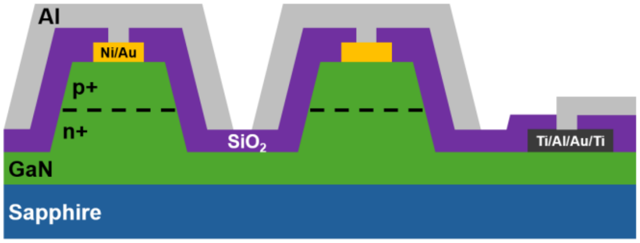

**Figure 2.** Diagram of the cross-section of two microLED stripe elements showing the anode, cathode, and low-resistance interconnect / reflector layer strategy.

***Fabrication:*** The light source array is fabricated starting from a GaN-on-sapphire epitaxial LED wafer. The basic structure of this wafer is a sapphire substrate, covered by a GaN buffer layer, on top of which an n-type GaN cathode layer is grown, followed by a series of InGaN/GaN quantum wells for efficient light emission, and finally a p-type GaN anode layer. The first fabrication step is the deposition of an anode contact metal stack of Ni/Au (20 nm/50 nm) via electron beam evaporation. After lift-off patterning, the sample is annealed at 550°C for 2 minutes under equal $N_2/O_2$ gas flow. Next, the individual pixels of the light source are formed by a $Cl_2/BCl_3$ reactive ion etching (RIE) process, selectively removing the top p-type GaN layer and exposing the underlying n-type material. With access to the n-type GaN, the cathode metal stack of Ti/Al/Au/Ti (20 nm/50 nm/100 nm/5 nm) is electron beam deposited and patterned. At this point, to prevent anode to cathode shorts in the upper metal layers to come, an interlayer dielectric layer of 550 nm $SiO_2$ is deposited using a 300°C plasma-enhanced chemical vapor deposition (PECVD) process. To gain access to the anodes and cathodes where desired, a second RIE process then takes place, this time

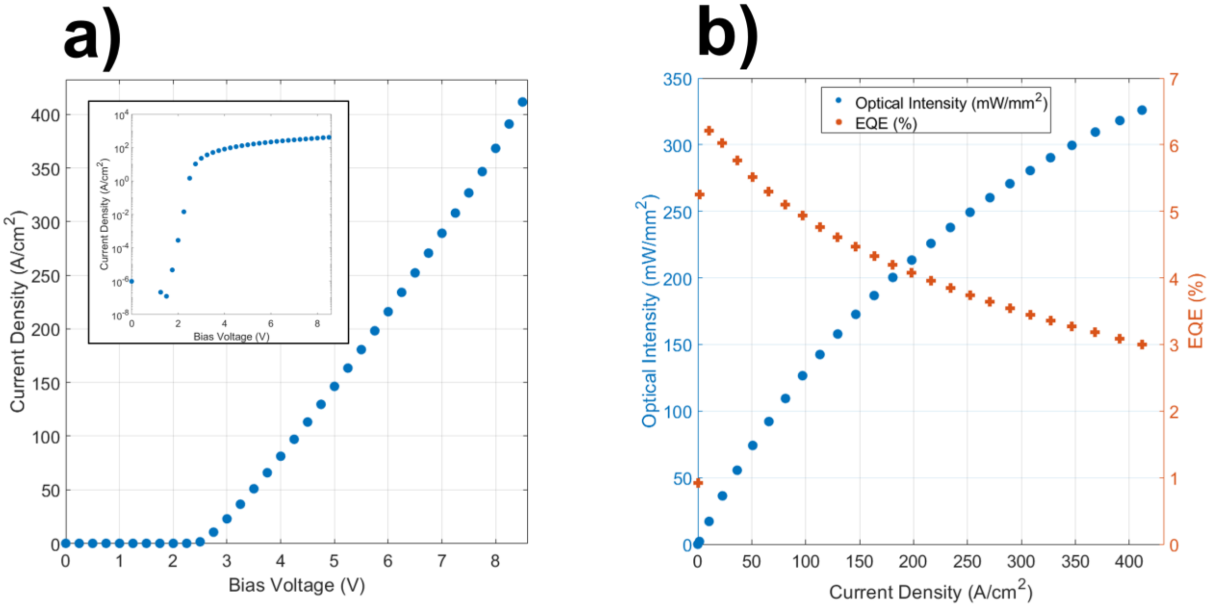

**Figure 3.** a) Current density vs. voltage characteristic of a single microLED stripe on the array. b) Light output intensity and external quantum efficiency of the stripe plotted vs. current density.

using Ar, $CH_4$, and $CF_4$ gases to open vias in the interlayer dielectric. Finally, the top metal layer of 500 nm Al is sputtered onto the sample and patterned with a final $Cl_2/BCl_3$ RIE step. This thick Al layer serves several purposes, acting as a low-resistance interconnect, light reflector, and bond pad material for connection to a carrier PCB. Lastly, individual chips are diced out of the larger processed substrate.

## 3. Results

After the fabrication is completed, the arrays are characterized by their light-current-voltage characteristics. In Figure 3 a), the IV curve of a single stripe is presented, with a logarithmically scaled plot of the same data in the inset. The curve indicates that the forward voltage of the microLED is approximately 2.5 V. In addition, it can be seen from the plot that when the junction is biased above the forward voltage, the current seems to depend approximately linearly on the voltage as opposed to exponentially as expected for an ideal LED. This suggests that there is a significant series resistance, likely arising either in the across-chip interconnects or at the anode-GaN or cathode-GaN interfaces. Figure 3 b) shows the light output intensity and external quantum efficiency of the stripe. The light output is measured by placing the chip on the surface of a Thorlabs S120VC photodiode power sensor. Due to the sufficiently large aperture of the photodiode and small area of the emitting stripe as well as the short distance between them, it is approximated that all of the bottom emitted light from the microLED is gathered by the photodiode. In this way, the light intensity as well as the EQE can be calculated and a peak intensity of 326 mw/mm$^2$ is measured. The maximum EQE is 6.2%, occurring at a bias current density of 10.4 A/cm$^2$. As expected, the EQE does decrease with increasing current density, falling to 3% at 411 A/cm$^2$.

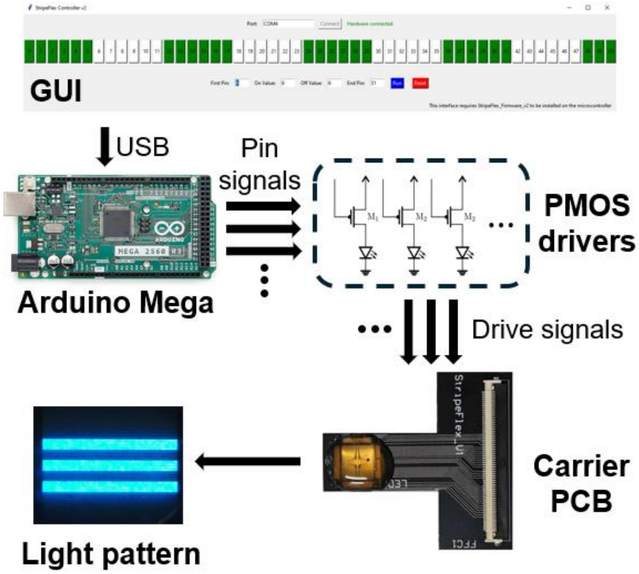

**Figure 4.** System diagram to show signal flow from the GUI programming leading to the appearance of the specified illumination pattern on the array.

After validating the performance of single stripes, the array is wire-bonded to a carrier printed circuit board (PCB). The carrier PCB is then connected to a control PCB via a 64-channel flat flexible cable (FFC) for sending enable signals to each stripe as well as providing a ground path. The control PCB houses an Arduino Mega 2560 microcontroller which is programmed by a custom Python-based graphical user interface (GUI) running on a computer. Upon receiving commands from the GUI software, the microcontroller programs the states of its pins and biases the gates of a bank of PMOS drivers to set the illumination pattern on the display. Figure 4 shows the block diagram of the light source controller system and Figure 5 exhibits the ability of the light source to be programmed to display various striped patterns suitable for OS-SIM imaging.

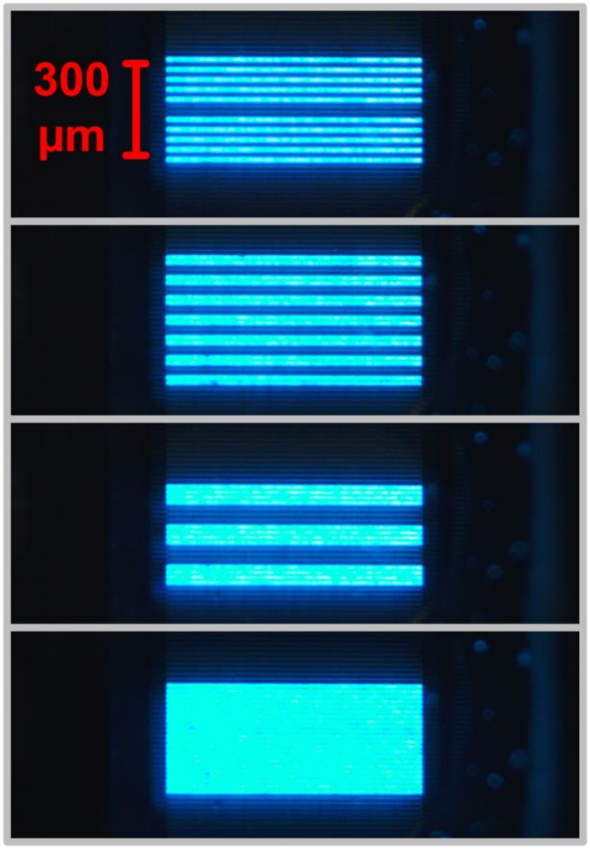

**Figure 5.** Demonstration of the light source displaying various striped patterns as well as a fully illuminated pseudo-widefield mode.

In Figure 6, the emission uniformity down the length of the stripes and the contrast between the "on" and "off" regions of the pattern are evaluated. Examining the plot of intensity along the length of the stripes shows that there is not a significant droop at either end or the center of the stripe indicating that the low-resistance interconnect layer is performing adequately. The intensity profile taken transversely across each group of stripes shows a high intensity in each illuminated group, surrounded by low intensity for the non-illuminated groups of stripes. For this pattern of 5 on, 7 off, 5 on, the average normalized intensity in the "on" regions is 0.66, while the average in the "off" region in between is 0.061. This results in a contrast ratio of 10.8:1. It is noted, however, that the exact contrast ratio measured will depend on the pattern selected. It can also be seen from the transverse profile, that there is a spike in intensity every 20 µm in the "off" region which is likely caused by the reflection of light off the sides of non-illuminated stripes.

## 4. Conclusions and Future Work

This work demonstrates a microLED light source and controller system that may be used in miniaturized OS-SIM setups, especially relevant to the application of neural imaging. The light source has an 80% fill factor, consisting of an array of 51 bottom-emitting microLED stripes each being 1016 µm long and 16 µm wide at a pitch of 20 µm. The maximum irradiance of the light source is 326 mW/mm$^2$ and the EQE ranges between roughly 3% - 6% depending on the bias current density. Light emission down the length of any given stripe is relatively uniform, not suffering from droop far from where the current is injected. The contrast ratio of the measured test pattern is 10.8:1. Optical crosstalk between neighboring stripes is suspected to be the root cause of this modest contrast.

In future iterations, we aim to improve this system by increasing the intensity of the emitted light. This may be achieved through several methods, such as improving the reflectivity of the mirror layer or performing treatment on the mesa sidewalls to reduce the effects of nonradiative recombination on the dry etched surfaces. Additionally, a black matrix may be introduced between the stripes to reduce pixel-to-pixel crosstalk and improve contrast in the generated illumination patterns, thus improving contrast in reconstructed OS-SIM images. Finally, we hope to work with collaborators to integrate this light source into an OS-SIM microscope system and test its imaging capabilities.

## 5. Acknowledgments

The authors acknowledge the funding support by the National Institutes of Health (R01 NS123665, R21 EY029458) and the National Science Foundation (1926747). Further, we would like to thank Zicong Huang for his careful photography. This work was carried out in part in the Columbia Nano Initiative Clean Room and Shared Materials Characterization Laboratories at Columbia University.

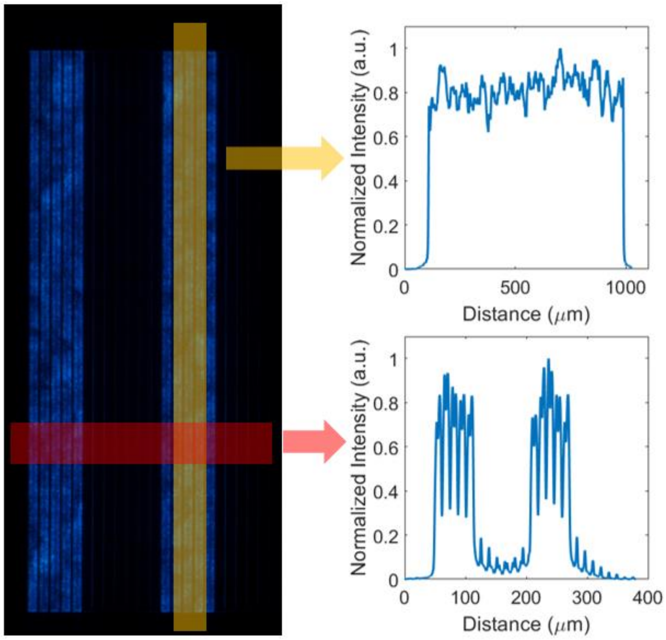

**Figure 6.** Intensity profiles of the light emission down a set of stripes (yellow) and across an on-off-on pattern of stripes (red). Note that a 2 µm width moving average filter has been added to the plotted profiles.

## 6. References

1. Alivisatos AP, Chun M, Church GM, Greenspan RJ, Roukes ML, Yuste R. The Brain Activity Map Project and the Challenge of Functional Connectomics. Neuron. 2012 Jun21;74(6):970–4.
2. Combs CA, Shroff H. Fluorescence Microscopy: A Concise Guide to Current Imaging Methods. Curr Protoc Neurosci. 2017 Apr 1;79(1):2.1.1-2.1.25.
3. Neil MAA, Juškaitis R, Wilson T. Method of obtaining optical sectioning by using structured light in a conventional microscope. Opt Lett. 1997;22(24):1905–7.
4. Dan D, Lei M, Yao B, Wang W, Winterhalder M, Zumbusch A, et al. DMD-based LED-illumination Super-resolution and optical sectioning microscopy. Sci Rep. 2013;3.
5. Supekar OD, Sias A, Hansen SR, Martinez G, Peet GC, Peng X, et al. Miniature structured illumination microscope for invivo 3D imaging of brain structures with optical sectioning. Biomed Opt Express. 2022 Apr 1;13(4):2530–41
6. Bozinovic N, Ventalon C, Ford T, Mertz J, Flusberg B, Cocker E, et al. Fluorescence endomicroscopy with structured illumination. Opt Express. 2008 May 26;16(11):8016–25.
7. Chen Z, Yan S, Danesh C. MicroLED technologies and applications: characteristics, fabrication, progress, and challenges. Journal of Physics D: Applied Physics. 2021 Jan 15;54(12):123001
8. Poher V, Zhang HX, Kennedy GT, Griffin C, Oddos S, Gu E, et al. Optical sectioning microscopes with no moving parts using a micro-stripe array light emitting diode. Optics express. 2007 Aug 21;15(18):11196–6.
9. Zhang HX, Gu E, Jeon CW, Gong Z, Dawson MD, Neil MAA, et al. Microstripe-array InGaN light-emitting diodes with individually addressable elements. IEEE Photonics Technology Letters. 2006 Jul 26;18(15):1681–3
10. 1.Kumar V, Behrman K, Speed F, Saladrigas CA, Supekar O, Huang Z, et al. MicroLED light source for optical sectioning structured illumination microscopy. Optics Express. 2023 May 4;31(10):16709.
11. Behrman K, Kymissis I. Enhanced microLED efficiency via strategic pGaN contact geometries. Optics Express. 2021 Apr 28;29(10):14841.