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Early Defect Identification for Micro LED Displays via Photoluminescent and Cathodoluminescent Imaging

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Abstract

Ultra-high resolution micro light emitting diode (LED) displays are emerging as a viable technology for self-emissive displays. Several of the critical issues facing micro LED displays with millions of pixels are fidelity, process control, and defect analysis during LED fabrication and transfer. Here, we investigate two non-destructive test methods, photoluminescent and cathodoluminescent imaging, and compare them to electroluminescent images to verify LED fidelity and evaluate these methods as potential tools for defect analysis. We show that utilizing cathodoluminescent imaging as an analysis tool provides a rich data set that can identify and categorize common defects during micro LED display fabrication that correspond to electroluminescence. Photoluminescent imaging, however, is not an effective method for fidelity analysis but does provide information on dry etching uniformity.

Keywords

Micro LED; photoluminescence; cathodoluminescence; pixel transfer; defect analysis; quality control.

1 Introduction

Micro light-emitting diodes (micro LEDs) are a promising technology for next-generation displays given their high brightness and efficiency, color gamut coverage, and self-emissive design[1, 2, 3]. Several HD and UHD displays have been demonstrated as prototypes, but there have been few commercial micro LED displays [4, 5]. Most applications require red, green, and blue (RGB) pixel integration, which is currently not possible from a single epitaxially-grown LED wafer in a fully self-emissive design [6]. Green and blue emission are both typically from GaN epitaxial stacks with an $In_xGa_{1-x}N$ emissive layer where the indium alloy content dictates the bandgap [7]. The best performing red-emissive devices, however, come from InGaAs epitaxial stacks [8]. The inherent difficulties in integrating these different epitaxial stacks onto a single display backplane for RGB integration have spurred numerous research efforts to a solution that is both cost-effective and robust. Green and blue emission with monolithic integration has been shown by utilizing two emissive layers, the quantum confined Stark effect, and strain modulation [9, 10, 11]. Fundamental differences in the growth methods and substrate requirements of InGaN and InGaAs complicates monolithic integration, with selective area epitaxy through nanowire growth being a notable exception [12].

To overcome this limitation, several transfer methods have been proposed to allow integration of singulated micro LEDs from red, green, and blue LED wafers onto a single wafer or backplane[3, 13, 14, 15, 16]. Given the 8.3 million pixels in an ultra-high-definition (UHD) display, these transfer methods can require up to 25 million micro LED transfers per display for RGB integration. The high number of transfers require 99.999999 % yield throughout the entire fabrication process to produce displays with a 75% final yield with no inactive pixels. Lesser fabrication yields result in a higher percentage of displays with inactive pixels, requiring the display to either be discarded or repaired [17]. Both add to the total fabrication cost of the display, and the latter may not be possible depending on the device architecture.

Inactive pixels can result from many defect mechanisms throughout the fabrication process. For instance, transfers can fail due to LED damage during the transfer process or improper seating of the LED to the backplane. In addition, improper passivation of the LED sidewalls can result in short-circuits between the cathode and anode, and chlorine-based dry etching-related damage

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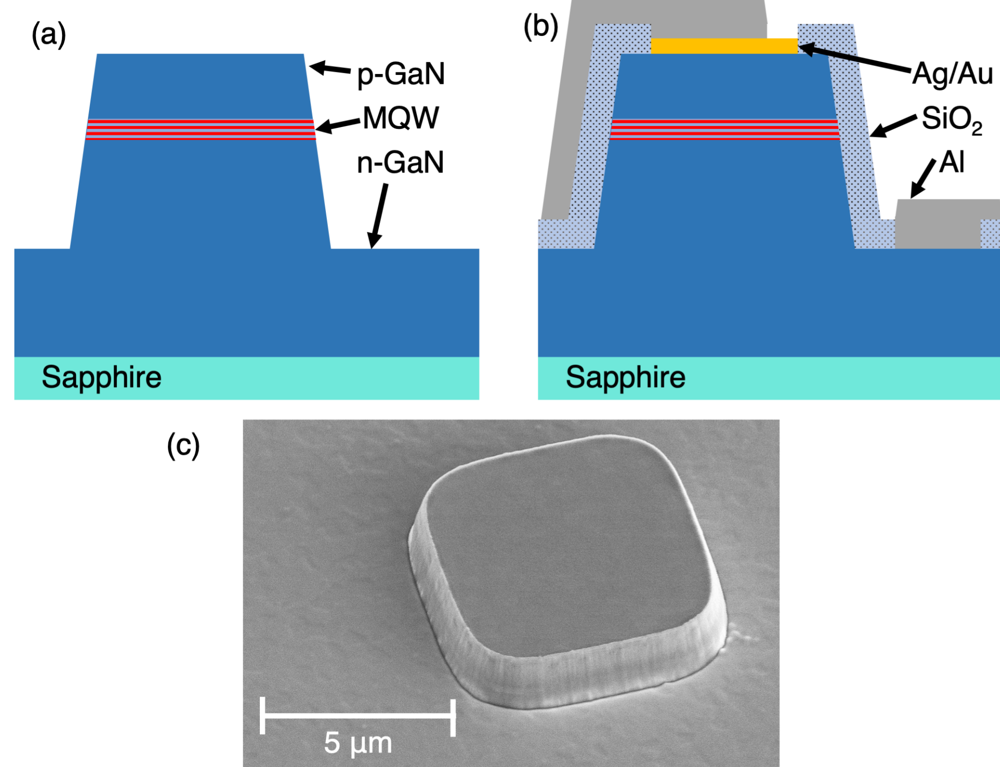

Figure 1: Device design. (a) Cross-section schematic of a single LED after dry etching. (b) Cross-section schematic of a single LED after passivation and metal wiring. (c) SEM image of a 5x5 μm^2 LED after dry etching the mesa structure as depicted in Fig. 1a. [18].

to the LED during mesa formation or redeposited GaN/GaAs related compounds can also cause short-circuits [19, 20, 21]. Defects in the wiring or interconnects can also cause inactive pixels. For many of these defects, the primary method of defect analysis is electroluminescent (EL) imaging and optical quality assurance checks [22, 23]. Unfortunately, this cannot be performed until the display is fully assembled and then must either be discarded or repaired. A non-destructive method to examine for pixel damage would significantly improve yield and fabrication quality while reducing manufacturing costs. Photoluminescent (PL) imaging has been utilized as a metrology and diagnostic tool for semiconductor devices to characterize photoemission and charge carrier properties [24, 25, 26, 27]. It has also been utilized as a defect diagnostic tool for semiconductor devices, poising it as a promising methodology for defect detection in micro LEDs. [28]. Cathodoluminescent (CL) imaging is similarly a useful imaging tool for mapping bandgap properties of nano and low-dimensional devices [29, 30, 31]. Here we investigate the viability of PL and CL imaging as two non-destructive test methods for short-circuit related defects in micro LED displays.

2 Experimental methods and fabrication

We used commercially available blue LED wafers (448 nm center wavelength) of epitaxially grown GaN and InGaN on micro-patterned sapphire for this study. The epitaxial growth stack consists of undoped GaN, n-type GaN, multiple quantum wells (MQWs), and p-type GaN. Each quantum well contains a few nm thick InGaN emissive region contained between undoped GaN

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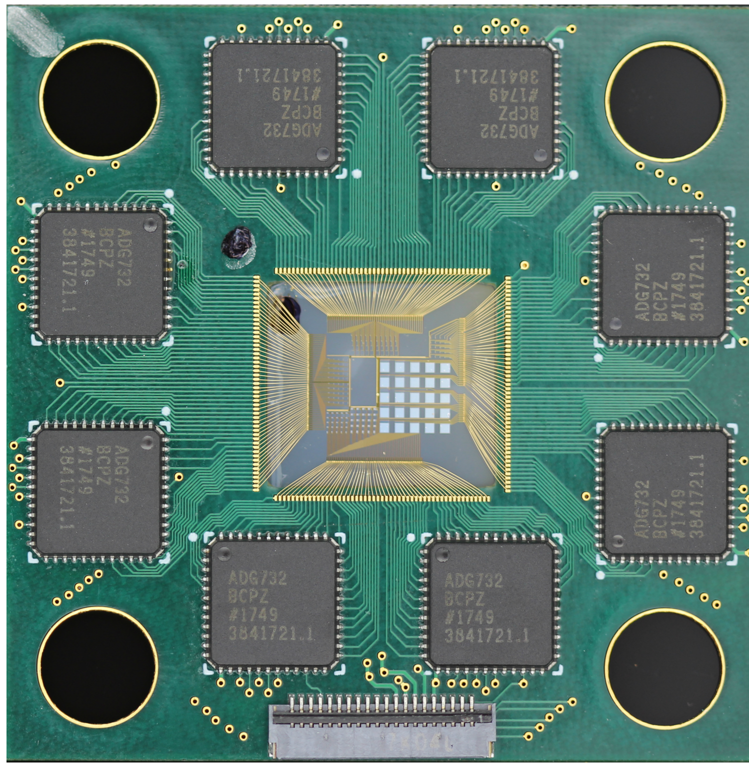

Figure 2: Multiplexer PCB with attached and wirebonded die for EL imaging [18].

barriers. Wafers were first thinned by mechanical grinding to approximately 200 μm thick and stealth diced into 10x10 mm^2 dies for processing. Each die was then coated with 500 nm of PECVD SiO_2 to be used as a hard mask during LED formation. The SiO_2 was coated with LOR 5A and S1805 for a bi-layer resist lift-off process. The resist was patterned using a DWL 66+ in direct writing mode to produce 200 square LEDs per die with side lengths of 5, 10, 15, 20, 25, 50, 100, and 500 μm. There are 25 of each LED size per die. 50 nm of chrome was e-beam deposited and lifted off in a solvent bath. The SiO_2 hard masks were patterned in an Oxford 100 dry etcher using CHF_3 and argon gases. The remainder of the chrome was wet etched before GaN etching to prevent contamination of the LED sidewalls from redeposited chrome. The GaN was then dry etched using a mixture of Cl_2 and BCl_3 to a depth of 1100 nm to expose the n-GaN layer below the MQWs. The remainder of the SiO_2 was wet etched in 10:1 buffered oxide etchant (BOE). The samples were then cleaned with acetone and oxygen plasma before imaging. Fig. 1 shows a schematic and an SEM image of a pixel.

CL images were taken using a Zeiss Supra 35VP field-emission scanning electron microscope (FESEM). Images were taken using the secondary electron (SE) detector and a photomultiplier tube. Samples were fixed to a stub with the n-GaN electrically connected to ground via conductive carbon tape. The SE detector was used to locate and verify the LED structures and the photomultiplier tube detector was used to collect the CL images. Engelsen et al., have detailed this method in more detail here [32].

PL images were recorded using a LEICA SP8 stimulated emission depletion microscope. The excitation source was a 405 nm diode laser programmed to raster scan over the active area of the die. The 405 nm laser line is sufficiently powerful enough to excite electrons to the conduction band in the InGaN wells but does not excite the wider bandgap GaN. Images were acquired from the

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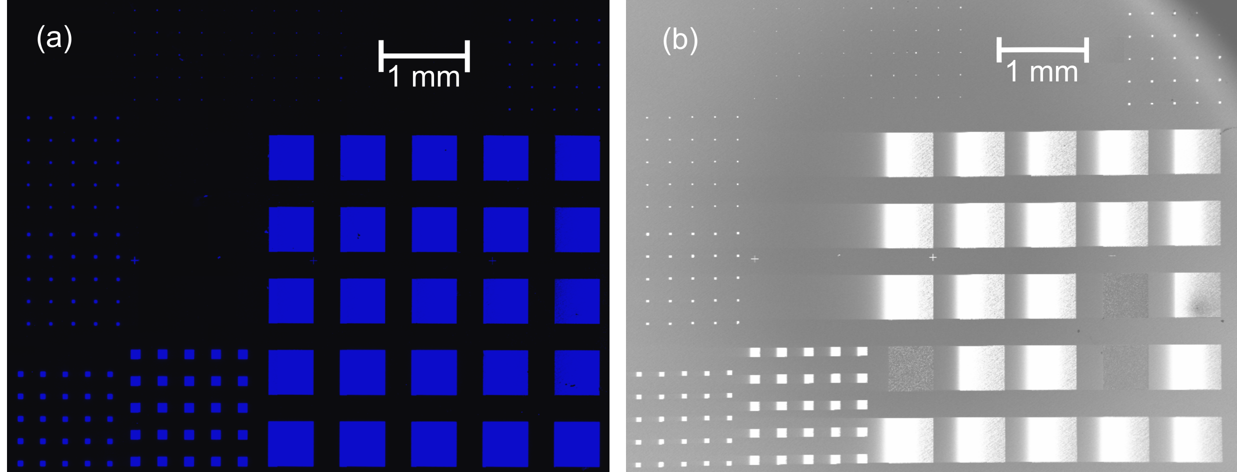

Figure 3: Non-destructive images. (a) PL composite image of 200 LEDs. Several images were stitched together to cover the entire device area. All LEDs are illuminated in this image. (b) CL SEM image of the same 200 LEDs from (a). While most LEDs exhibit emission, several are inactive [18].

photomultiplier tube sensor with a bandpass filter set between 425 and 475 nm to remove excitation source reflections and background noise. For both images, the number and location of the inactive pixels were recorded.

After both non-destructive images were collected, we continued device fabrication to compare these methods with EL imaging. First the samples were cleaned in Nanostrip followed by acetone, IPA, and DI water baths to remove any contamination from adhesive residue used in imaging. PECVD SiO_2 was deposited on the samples as a passivation layer. The SiO_2 was dry-etched with a photoresist mask to expose the n-type and p-type GaN layers for electrical contact. A bi-layer resist stack of LOR 30B and SPR220 4.5 was spin-coated and patterned for lift-off of 20 nm silver / 60 nm gold ohmic contacts to the p-GaN. After stripping the remaining photoresist, 300 nm of conformal sputtered aluminum was lifted off with the same bilayer stack to contact the n-GaN and to connect each p-GaN contact over the LED sidewall. Each pixel was addressed individually while using a common n-GaN contact instead of passive matrix addressing to prevent an entire row or column of pixels to be inactive from a single short circuit defect. Individual wiring, while more tedious, gives higher precision to the exact location of a defect. The samples were deposited with 5 nm chromium / 600 nm gold and lifted off to form wire bond pads at each contact. Finally, the samples were fixed to a printed circuit board (PCB) with adhesive and wire-bonded with a semi-automatic bonder. The finished device is shown in Fig. 2. The PCB contains multiplexers to address each LED controlled by a Teensy 3.6 microcontroller. The Teensy firmware programmed the current output from a Keithly 2410 source meter unit to each LED subarray of 25 devices. EL images were taken under a 5x microscope to verify device illumination. The inactive pixels were counted and compared to their respective PL and CL images.

After EL analysis, additional CL images were taken with the die still attached to the PCB. The common n-GaN contact was electrically connected to the stub of the SEM through a test point contact on the PCB. The individual p-GaN contacts were connected through the wirebonds to the inactive multiplexer integrated circuits (ICs) acting as a virtual ground current return path for the incident electrons. This provides a new measurement paradigm allowing multiple current return paths that results in images with a richer dataset.

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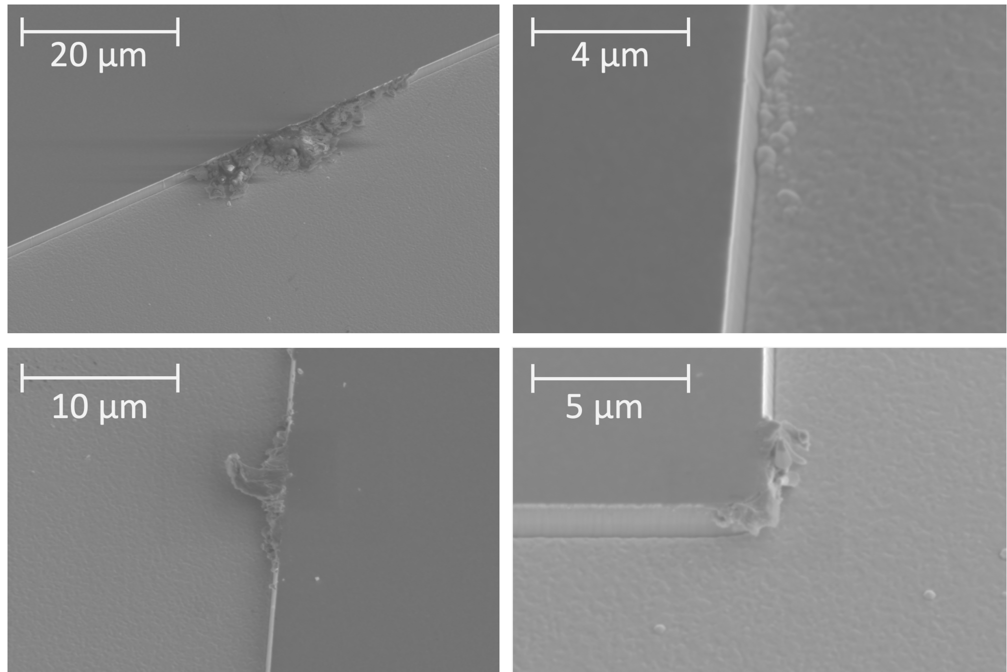

Figure 4: SEM images of pixel damage from dry etching [18].

3 Results and Discussion

The PL images show emission centered around 448 nm at the locations of the formed LEDs. An example PL image can be seen in Fig. 3a. The image shows 200 LEDs in a 6 x 5 mm^2 area. All 200 LEDs exhibit PL in this image. Note that the 5x5, 10x10 and 15x15 μm^2 pixels in the top row are all active but are difficult to see at this scale. We also observed illumination at the alignment marks and from scattered spots and defects throughout the die, even at locations far from the pixel structures. The scattered spots are composed of InGaN material that have either been created as particles from handling or areas of re-sputtered InGaN from the etching process. This shows that PL imaging can provide some information on dry-etching uniformity by analyzing PL emission outside of desired micro LED locations. Across the four individual dies, all 800 pixels exhibited PL after the dry etching step. This does not mean that PL imaging is predicting 100% yield but instead is an ineffective predictor of dry-etching related defects as first reported by Tesoro Scientific [22, 23]. This is further supported by CL and EL results discussed next that show lesser yields. We pose that PL excitation is not affected by short-circuit defects across the etched LED sidewall because of the lack of carrier transport. Electrons within the InGaN quantum wells are excited by the 405 nm light and show emission upon relaxation regardless of the presence of a short-circuit.

The CL images are panchromatic and are thus insensitive to spectra but display qualitative luminescent intensity. Quantitative comparisons between wafers or dies would be possible in a calibrated system but was not available due to image acquisition occurring over several days with multiple users. Fig. 3b shows an example image of the same die that is displayed in Fig. 3a. The areas in bright white represent strong luminescence. An LED with little or no luminescence is indicative of a defect causing an electrical short between the anode and cathode providing a shunt resistance current return path around the emissive InGaN MQWs. Otherwise, electrons injected from the FESEM's gun would return to ground through the InGaN layer and emission would be observed.

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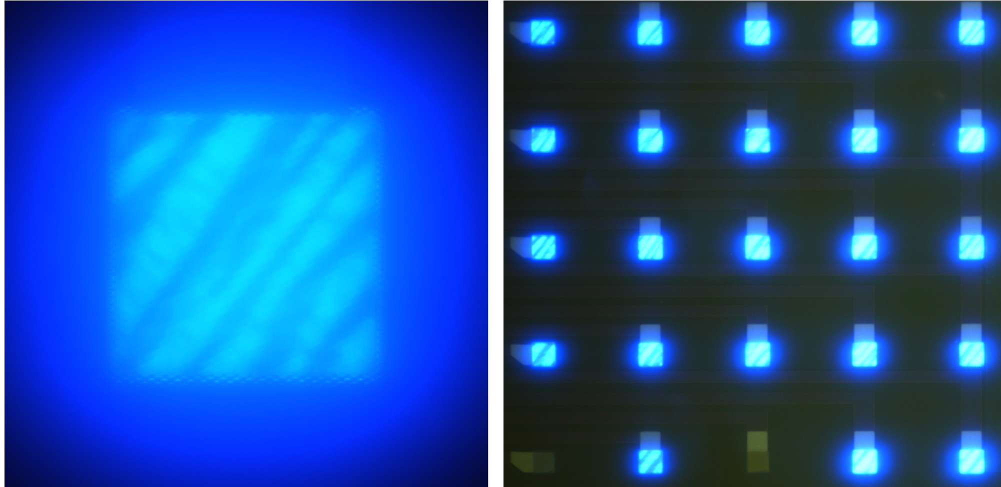

Figure 5: Electroluminescent images of a single 50x50 μm^2 pixel and an array of 50x50 μm^2 pixels [18].

We explored this phenomenon further by examining the edges of the inactive pixels under SEM with an SE detector. We were able to find various defects likely related to re-deposited material or micro-masking from defects in the SiO_2 etch or photoresist residue. Example SEM images of the defects can be seen in Fig. 4.

We recorded EL images of all pixels amongst all four dies. Fig. 5 shows example images of a single pixel and an array with both active and inactive pixels. Darkfield images were taken with the PCB mounted underneath a microscope objective focusing through the sapphire, also referred to as bottom emission. The EL active pixels have a distinct non-uniformity with a scattered bloom around the edges of emission. The non-uniformity is likely due to surface roughness variations caused from sapphire grinding during the thinning process. The scattered bloom is a result of the scattering microstructures built into the sapphire substrate. We compared the yield results from CL to EL to better understand their relationship. Pixels were examined as being active (luminescent) or inactive (non-luminescent) for both tests. Given this, there are four distinct pixel outcomes when compared with CL imaging:

- Active both with CL and EL - 71.75% of samples. This was the most common outcome and suggests that CL is an accurate predictor of EL performance.
- Active with CL but inactive with EL - 24.25% of samples. This was the second most common result and suggests no dry-etching-related damage, and further processing after CL imaging introduced additional defects, preventing EL.
- Inactive both with CL and EL - 3% of samples. This outcome suggests that a short-circuit defect was introduced during the dry etching stage of device fabrication and that CL is an accurate predictor of EL results from etching related damage.
- Inactive with CL but active with EL - 1% of samples. This was the least common result and suggests that nanostrip cleaning removed some etching-related damage, or that the sidewall passivation process inadvertently modified the surface to increase the shunt resistance. This is expected as sidewall passivation and chemical treatments have been shown to improve device performance [33, 34].

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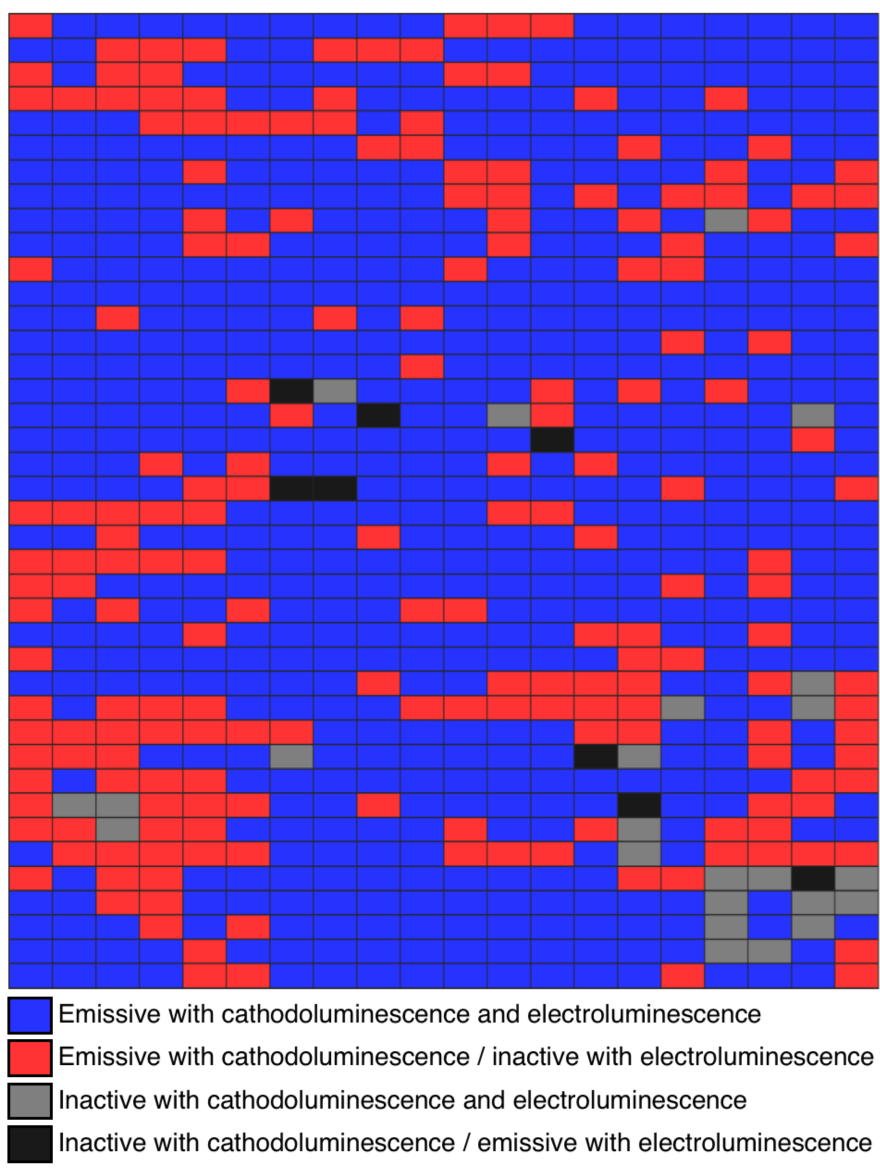

Figure 6: Heatmap of the yield results from all 800 examined pixels comparing the results of cathodoluminescence and electroluminescence [18].

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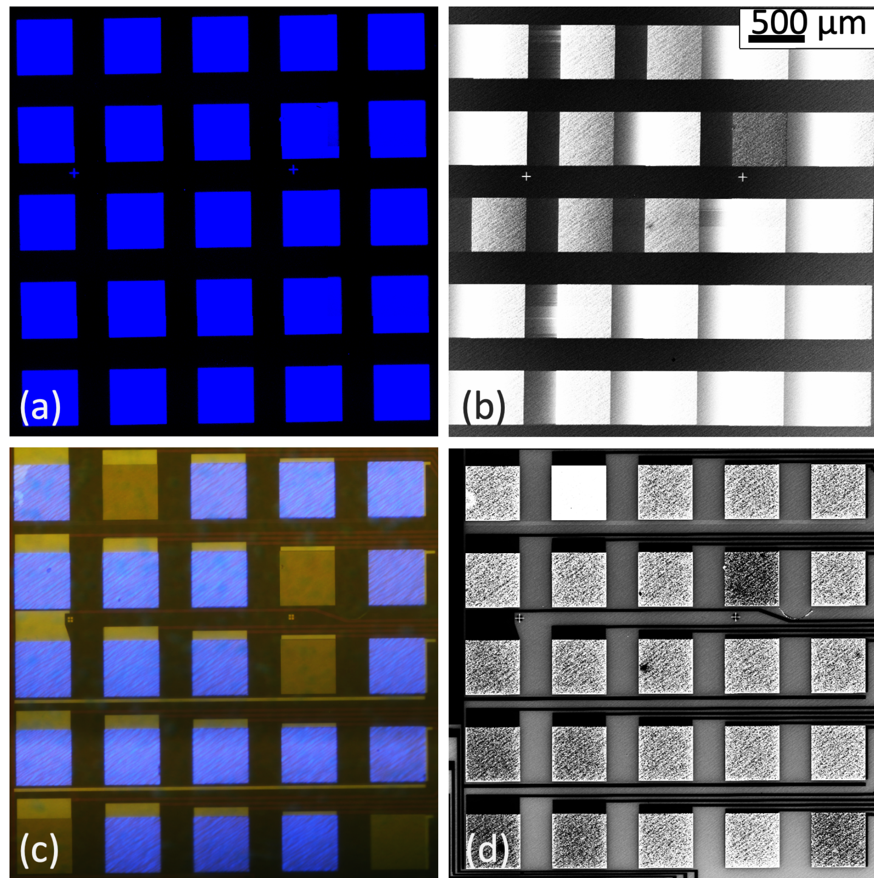

Figure 7: Twenty-five 500x500 μm^2 pixel images. (a) PL image after mesa etch. (b) CL image after mesa etch. (c) EL image after completed fabrication and die attach. (d) CL image after completed fabrication and die attach.

A summary of all of these outcomes is mapped in Fig. 6. All pixels were active in PL tests but these results were not consistent for CL and EL imaging. For this reason, PL results were not compared in Fig. 6.

The second most common result, active with CL but inactive with EL, can be explained due to the difficulty in handling small dies through several fabrication steps thus introducing further defects. Additionally, there was visible conductive adhesive residue from fixing the samples to the SEM chuck that was difficult to remove with further chemical processing that contaminated large numbers of pixels. These contaminated pixels were predominately inactive with EL imaging. Defects in the wiring of the pixels also caused EL failure.

We reexamined a subset of the devices with CL imaging with the die attached to the PCB. This represents a new measurement paradigm as the incident electrons from the FESEM gun are now being absorbed by the p-GaN metal contact rather than the p-GaN itself. With the contact metal at a higher potential, the path electrons use to return to a lower potential state depends on the defect state of each pixel.

To highlight this phenomenon, Fig. 7 shows twenty-five pixels with four non-destructive images. The PL images in Fig. 7a show uniform luminescence and predict no defects in this array. The CL images in Fig. 7b display a variety of contrast levels which we interpret as a reliability marker for a short circuit related defect for etching related damage. The majority of the pixels show very bright

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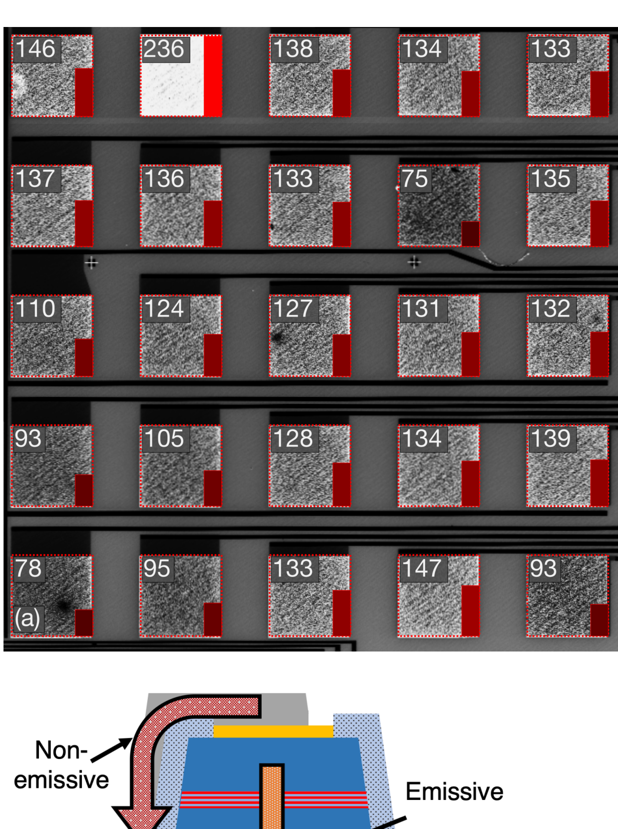

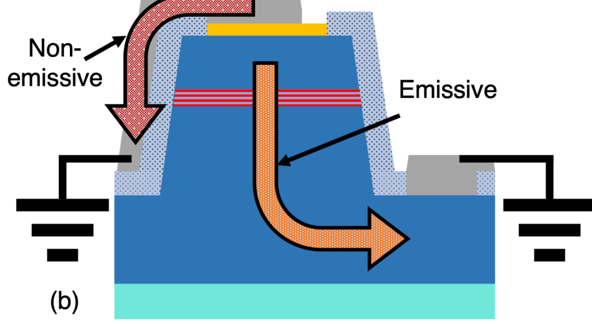

Figure 8: (a) Brightness analysis of CL data from the pixels in Fig. 7d. (b) Current return paths for incident electrons during CL imaging.

luminescence, predictive of no damage. Several pixels show intermediate brightness and one pixel shows very low brightness. The blurring effect seen is due to the long carrier lifetime in the InGaN MQWs and short pixel integration time as described in detail by Engelsen [32]. When compared to the EL image in Fig. 7c, we observe five defective pixels where only one defect is correctly predicted by CL imaging before fabrication completion, indicated by the low-brightness pixel.

Comparing CL images in Fig. 7b and d show stark differences in pixel illumination. One pixel in Fig. 7d is distinctly brighter than the remaining pixels. Most are of intermediate brightness and a few have diminished luminescence. Compared to the known defective pixels from Fig. 7c, we see that the brightest pixel and three of the dimmest pixels in Fig. 7d correspond to defects. One discrepancy is the dead pixel in the middle row of Fig. 7c does not seem to be predicted by either CL image.

To quantify the intensity of each pixel from Fig. 7d, we devised a simple script in MATLAB to measure the brightness of each pixel from marked regions of interest (ROI) as seen in Fig. 8a. The average intensity of all pixels within each ROI is overlaid on the pixel within a range from 0 to 255. These brightness values provide accurate predictions on the luminescent properties under EL and the defect state of each pixel. Pixels near the maximum brightness range indicate high amounts of

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optical recombination occurring in the InGaN, suggesting a minimum amount of current returning through the p-GaN contact to a virtual ground as represented in Fig. 8b. This suggests a defect in wiring or attachment to the p-GaN contact, as seen by a lack of luminescence in Fig. 7c. Pixels near the minimum brightness range indicate low amount of optical recombination suggesting a minimum amount of emissive current. This suggests either a shunt resistance across the emissive InGaN or a wiring defect with the n-GaN contact or wiring. Pixels sitting in the middle of the brightness range suggest utilization of both current return paths with no shunt resistance from dry-etching damage. The majority of the pixels fall within this range and correlate to the luminescent pixels in Fig. 7c.

Fig. 7 and 8 demonstrate the feasibility of accurate defect analysis of micro LEDs utilizing CL imaging. We demonstrated this technology with small batch devices fabricated in a university cleanroom with shared equipment. CL analysis was preformed in a conventional FESEM with a photomultipler detector and a semi-automated MATLAB script. We believe that scaling CL technology to wafer or panel sized fabrication equipment with automated image analysis would be a reliable technique for defect analysis in industrial mass production of micro LEDs.

4 Conclusion

Self-emissive micro LED displays still exist as an expensive and specific solution for niche applications due to the difficulty in producing displays with millions of pixels, with no inactive LEDs, and integrating multiple colors onto one backplane. By utilizing CL imaging, micro LED short-circuit defects from dry-etching-related damage causing individual pixels or LEDs to become inactive under EL can be reliably predicted. PL imaging can identify re-deposited InGaN from etching processes that could hinder further fabrication process steps. However, PL imaging fails to identify etching related damage causing LED short circuits. Additional wiring and contact defects are simply identified via CL imaging and brightness measurements. These two methods of CL pose as fast and non-destructive measurements to provide fidelity information for micro LED displays.

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6 Competing financial interest

Ioannis Kymissis is a board member of Lumiode, which is a start-up working in micro LED and holds an equity stake in the company.

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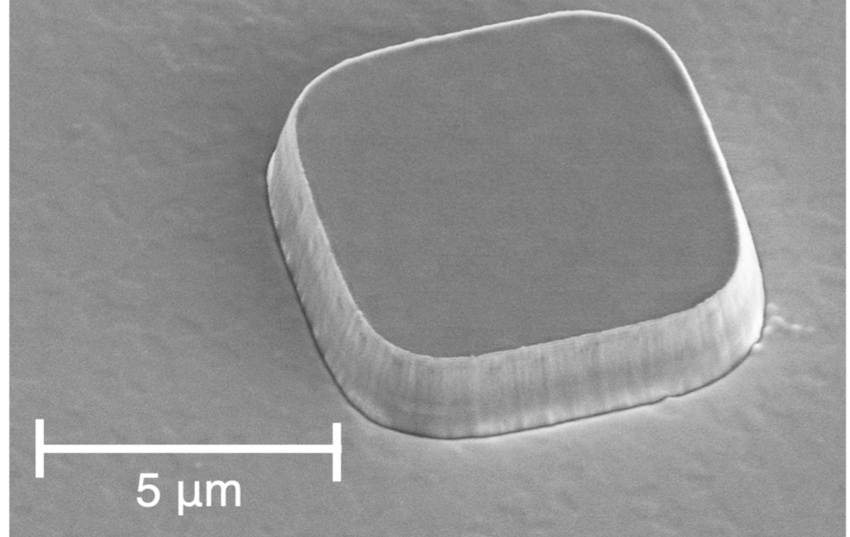
(a)
p-GaN
MQW
n-GaN
Sapphire

(b)
Ag/Au
SiO_2
Al
Sapphire

(c)



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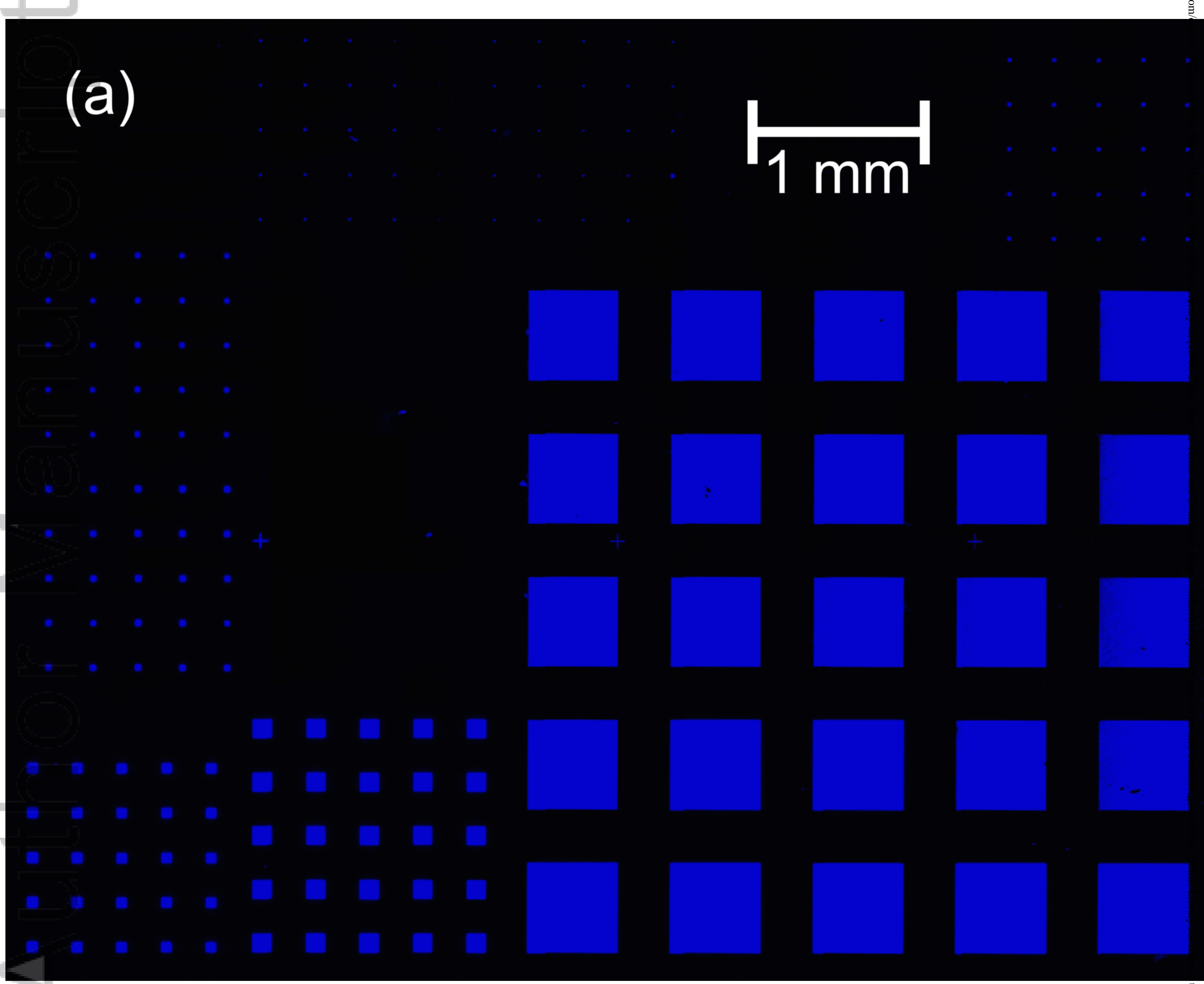

figure3a.png

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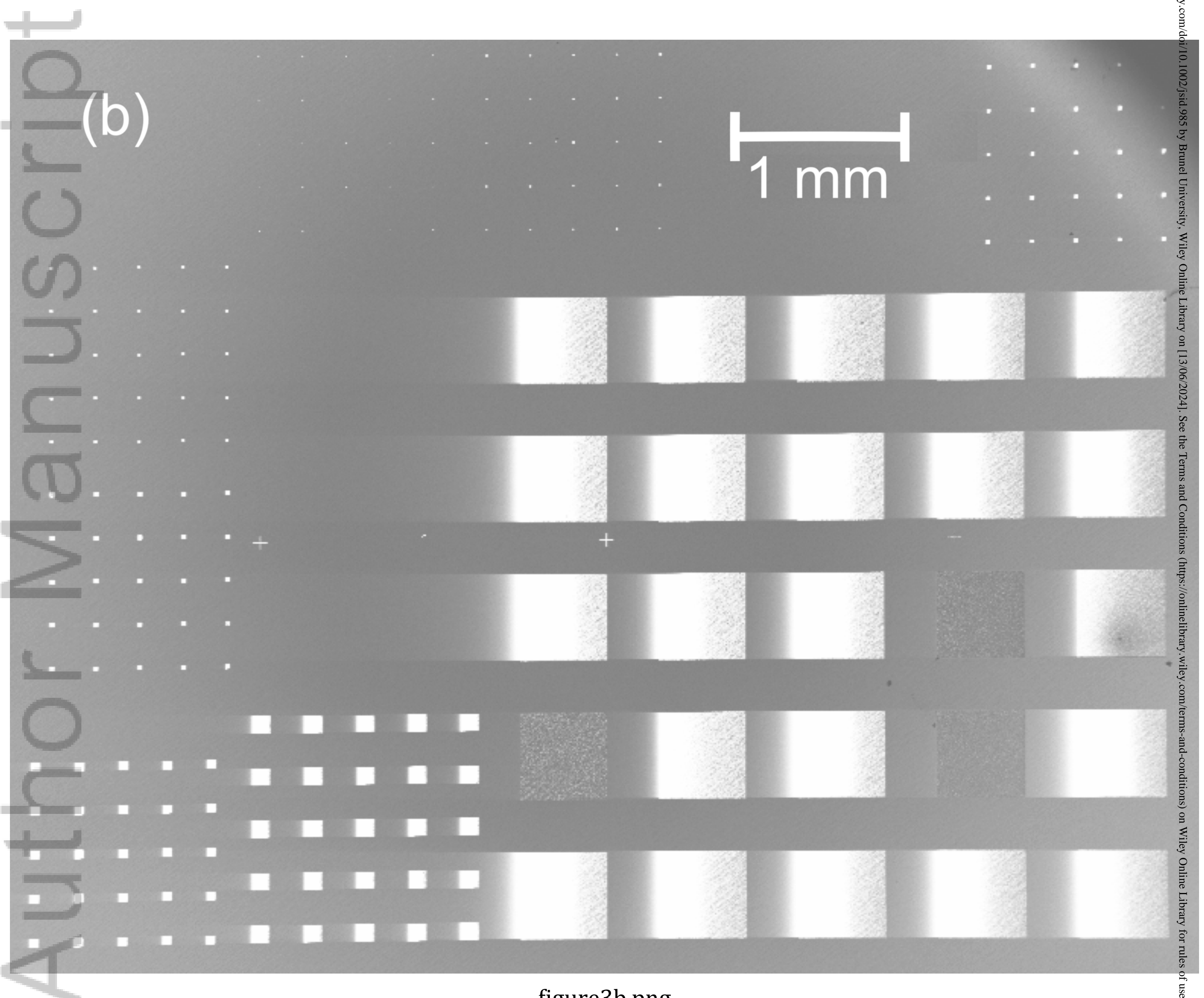

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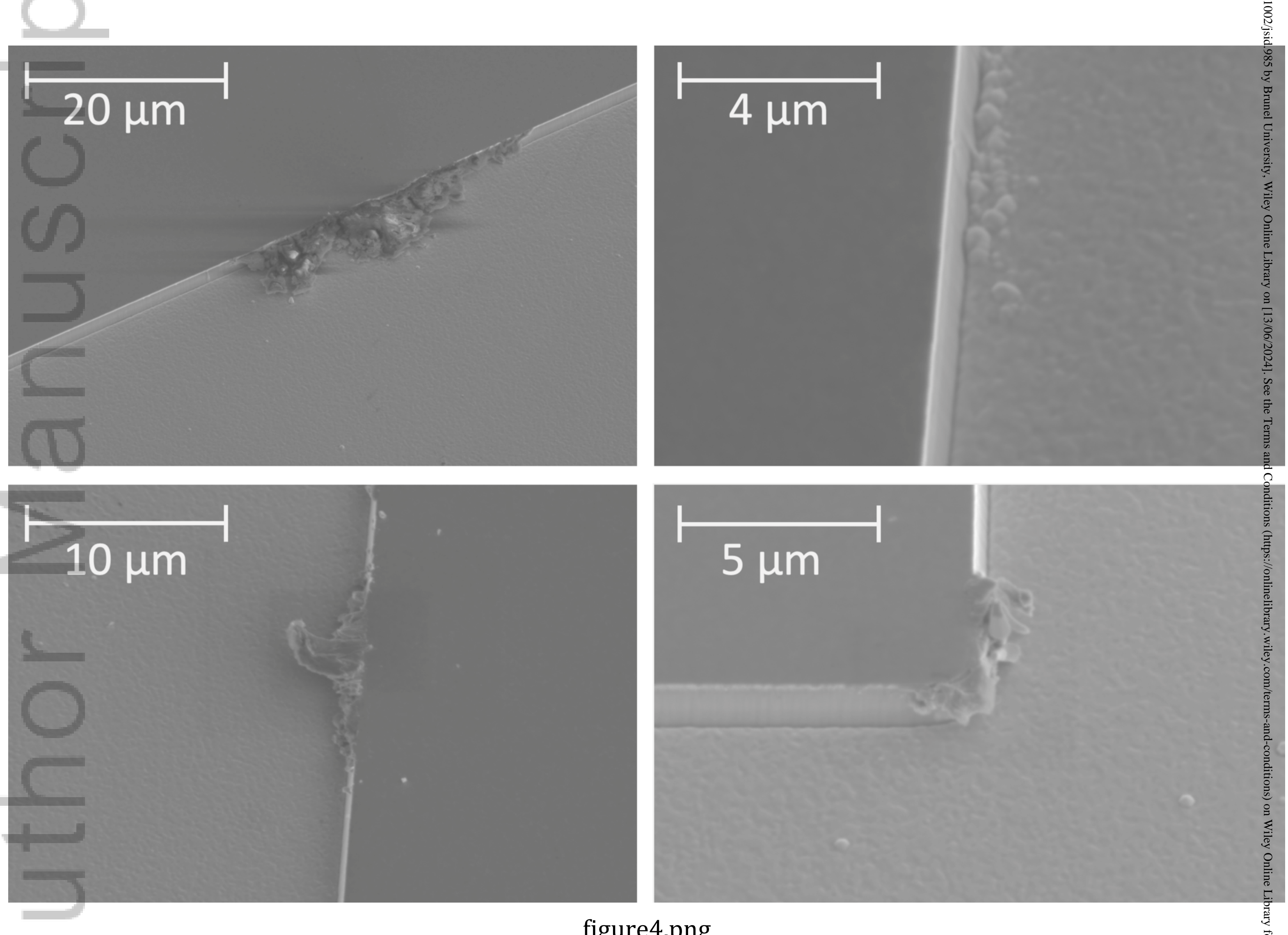

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figure5.png

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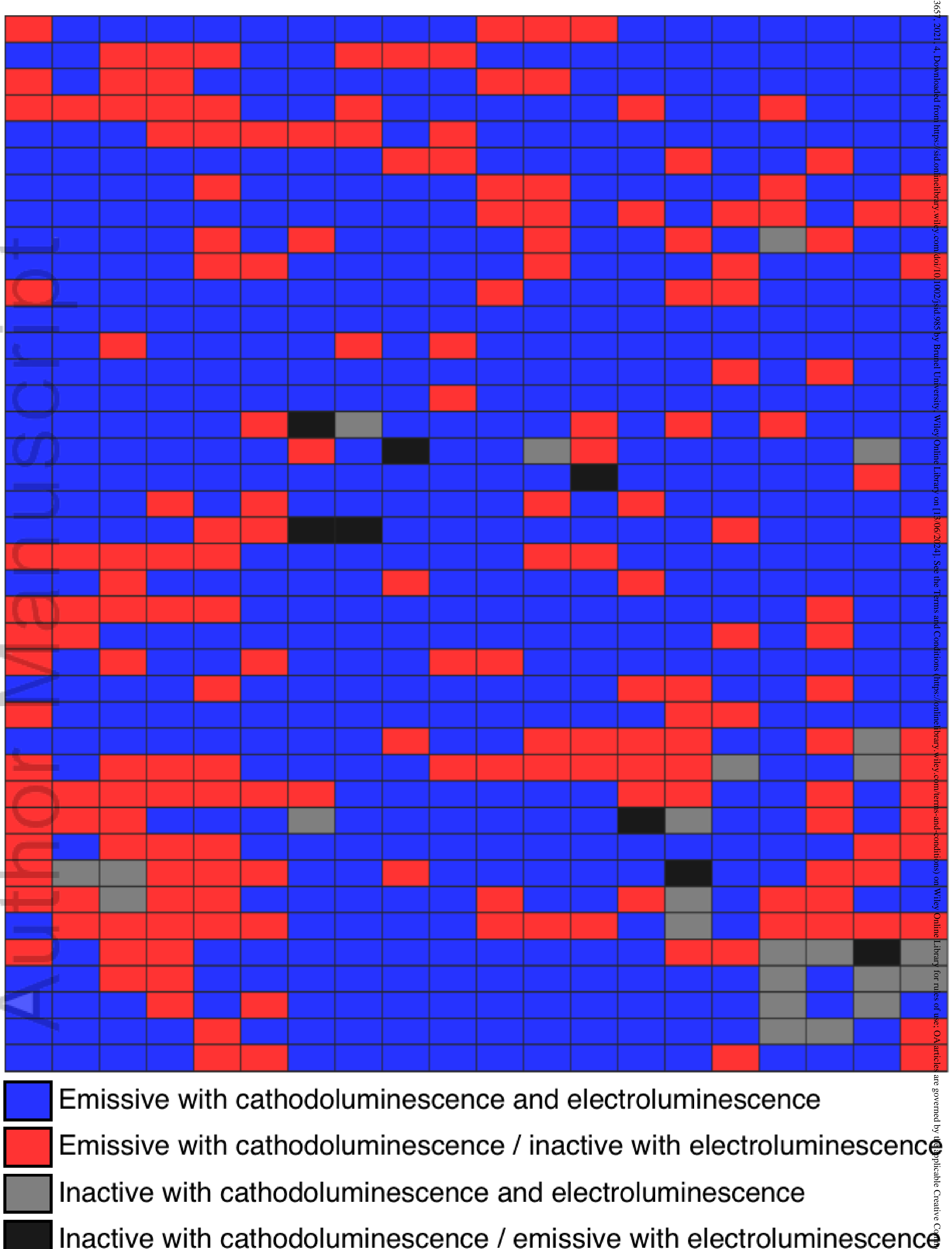

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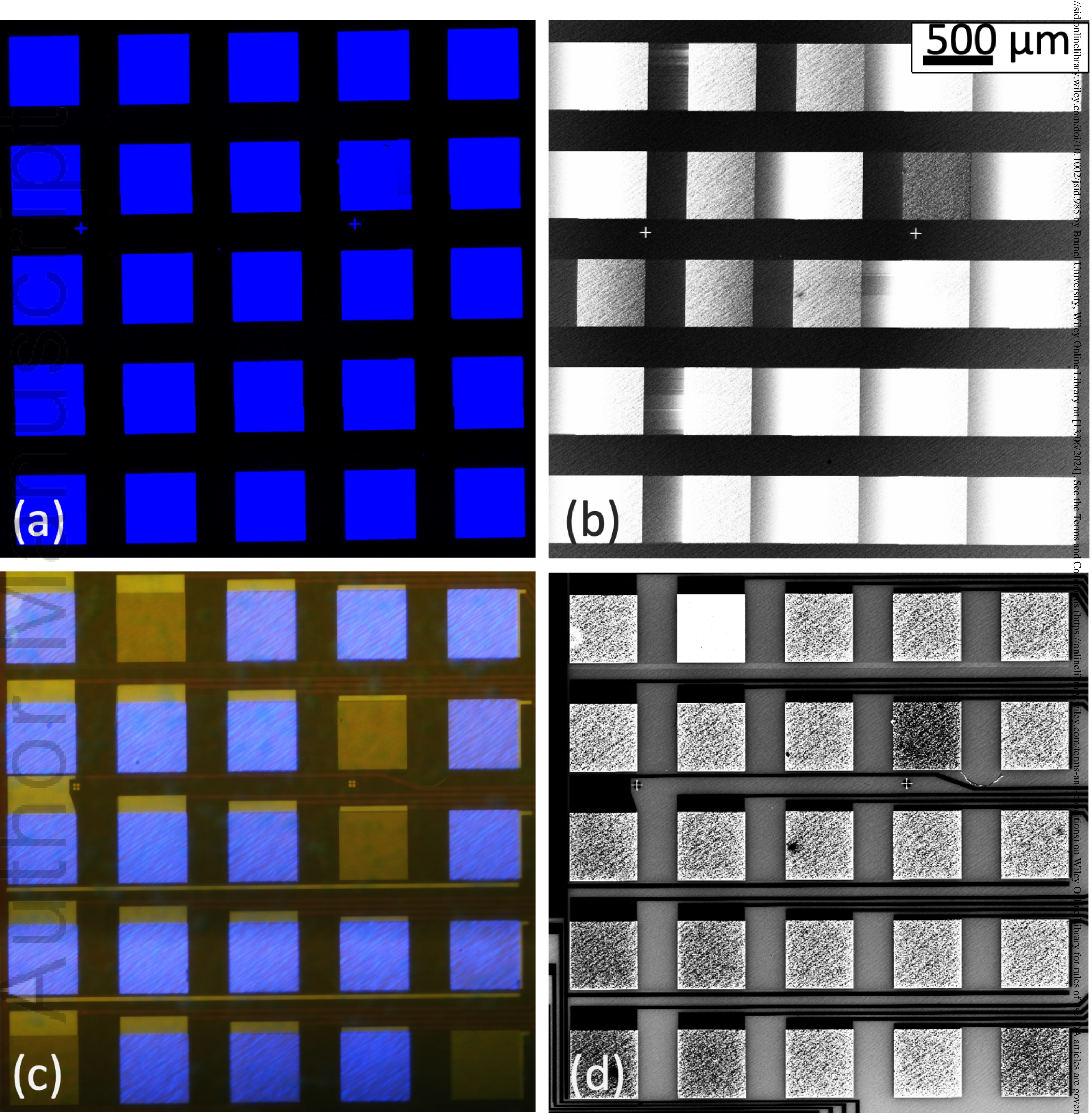

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figure8a.png

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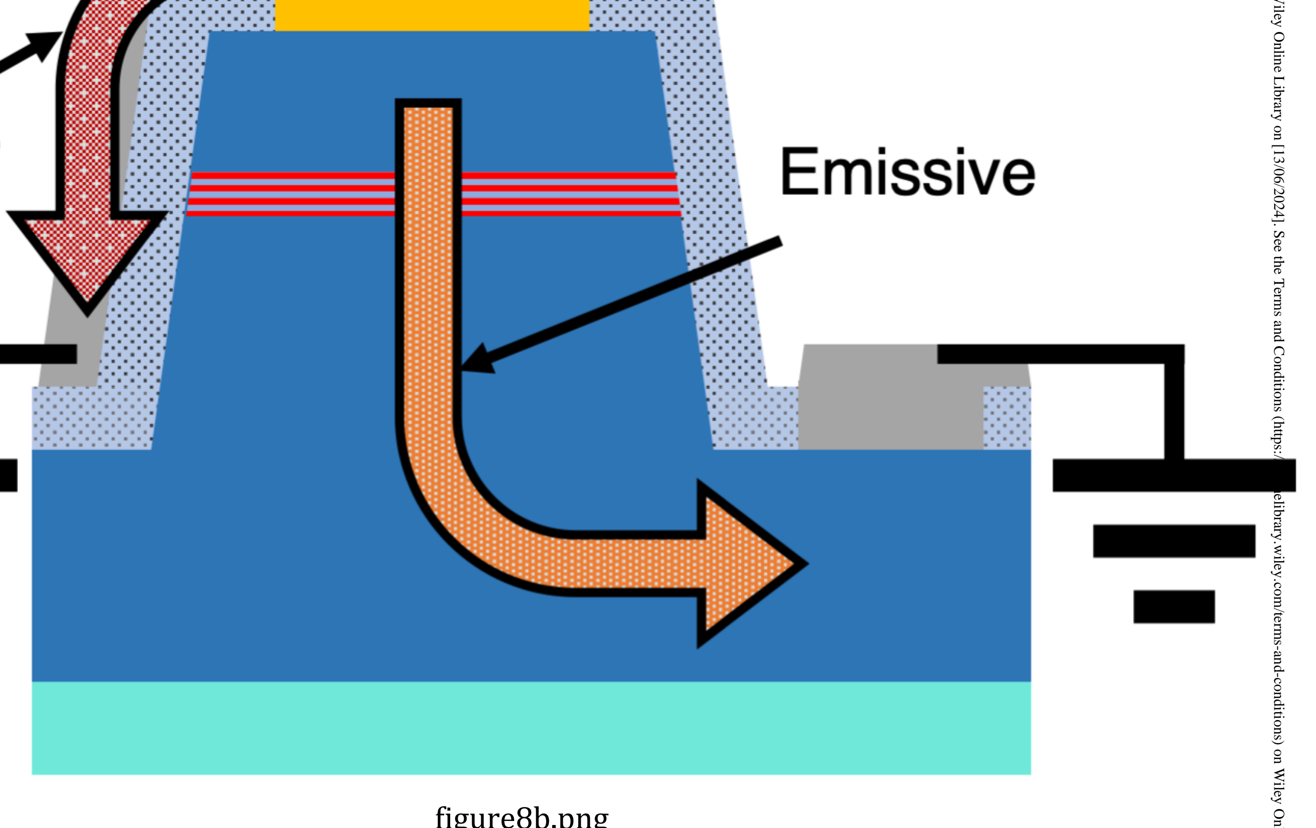

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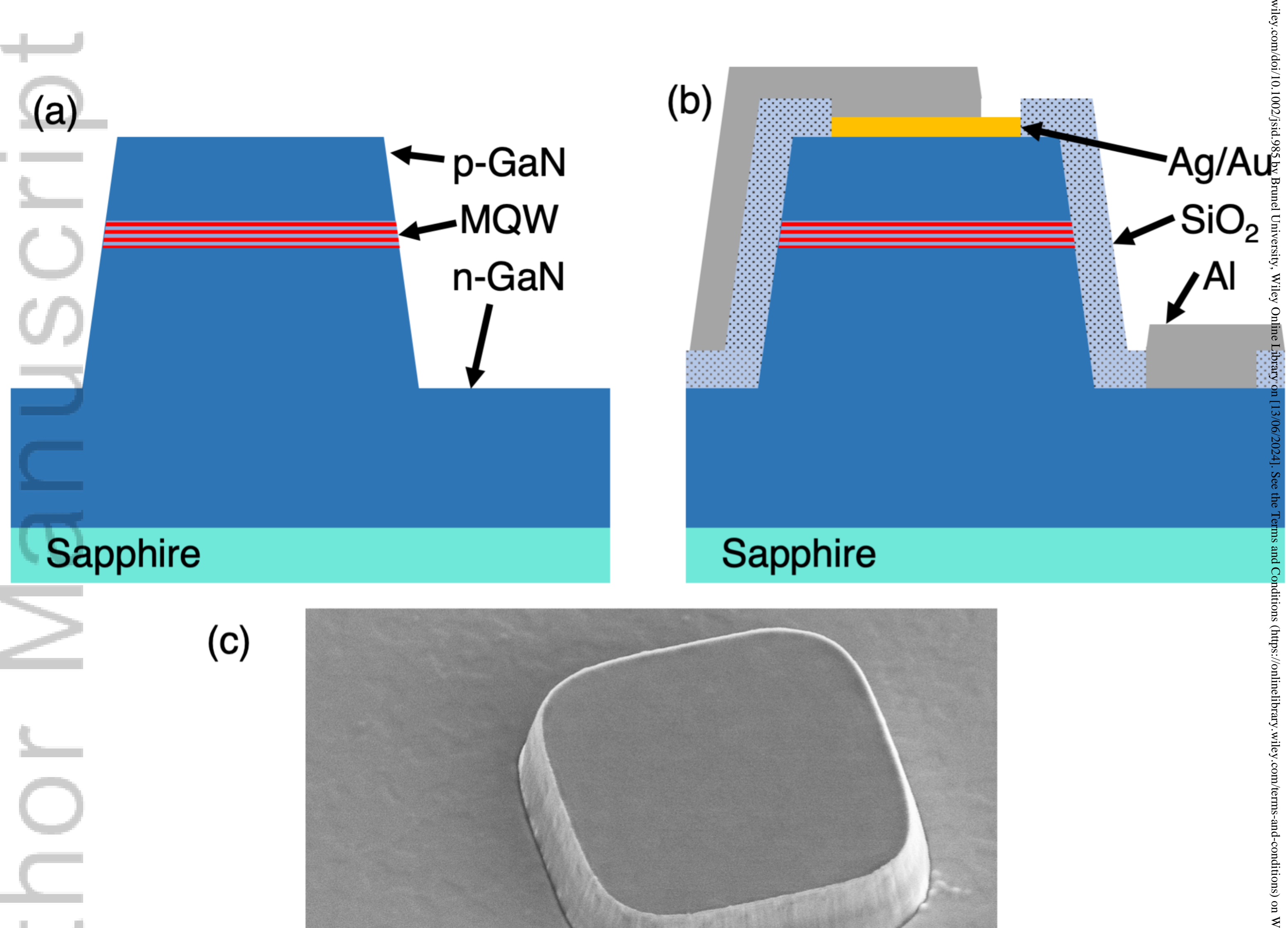

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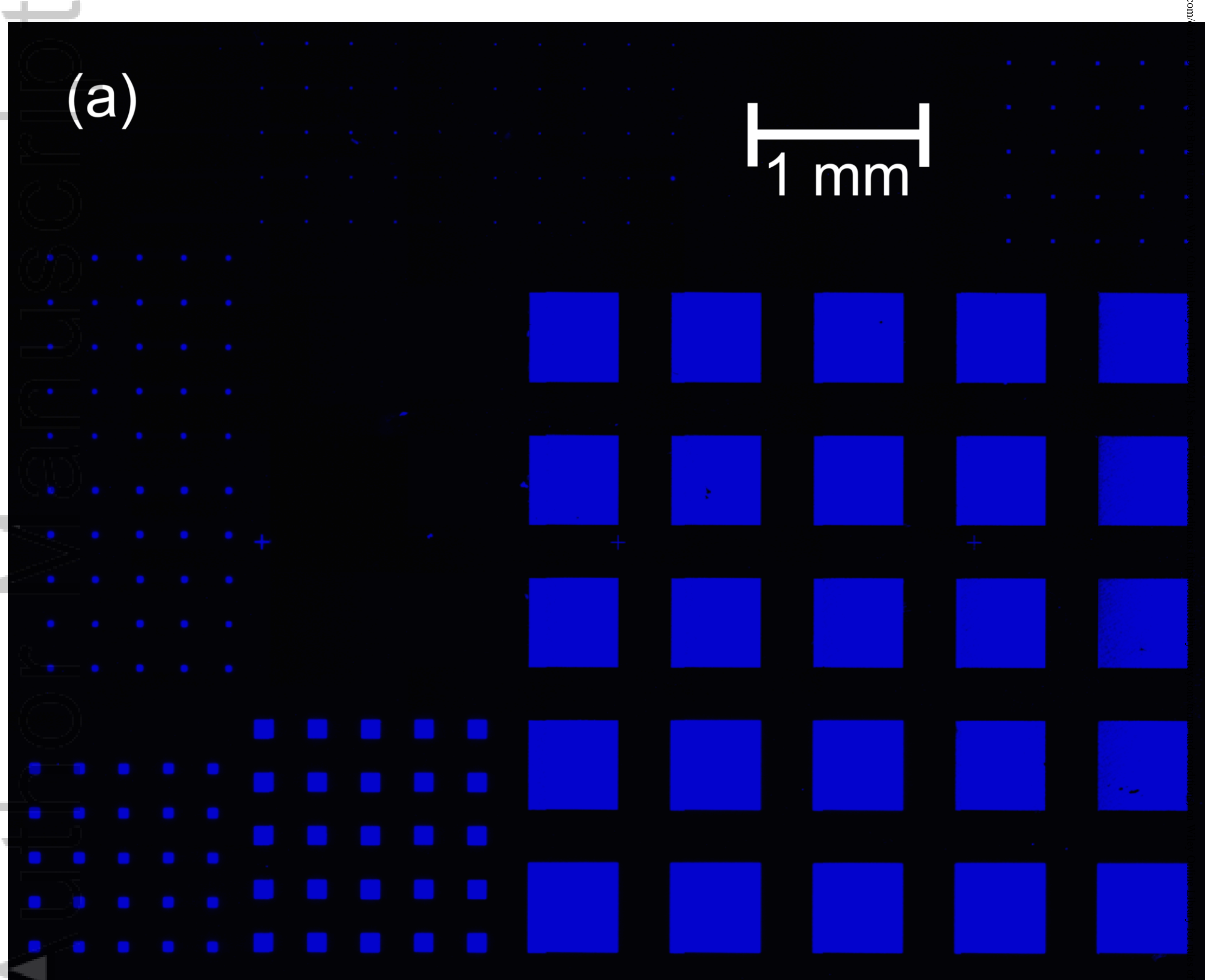

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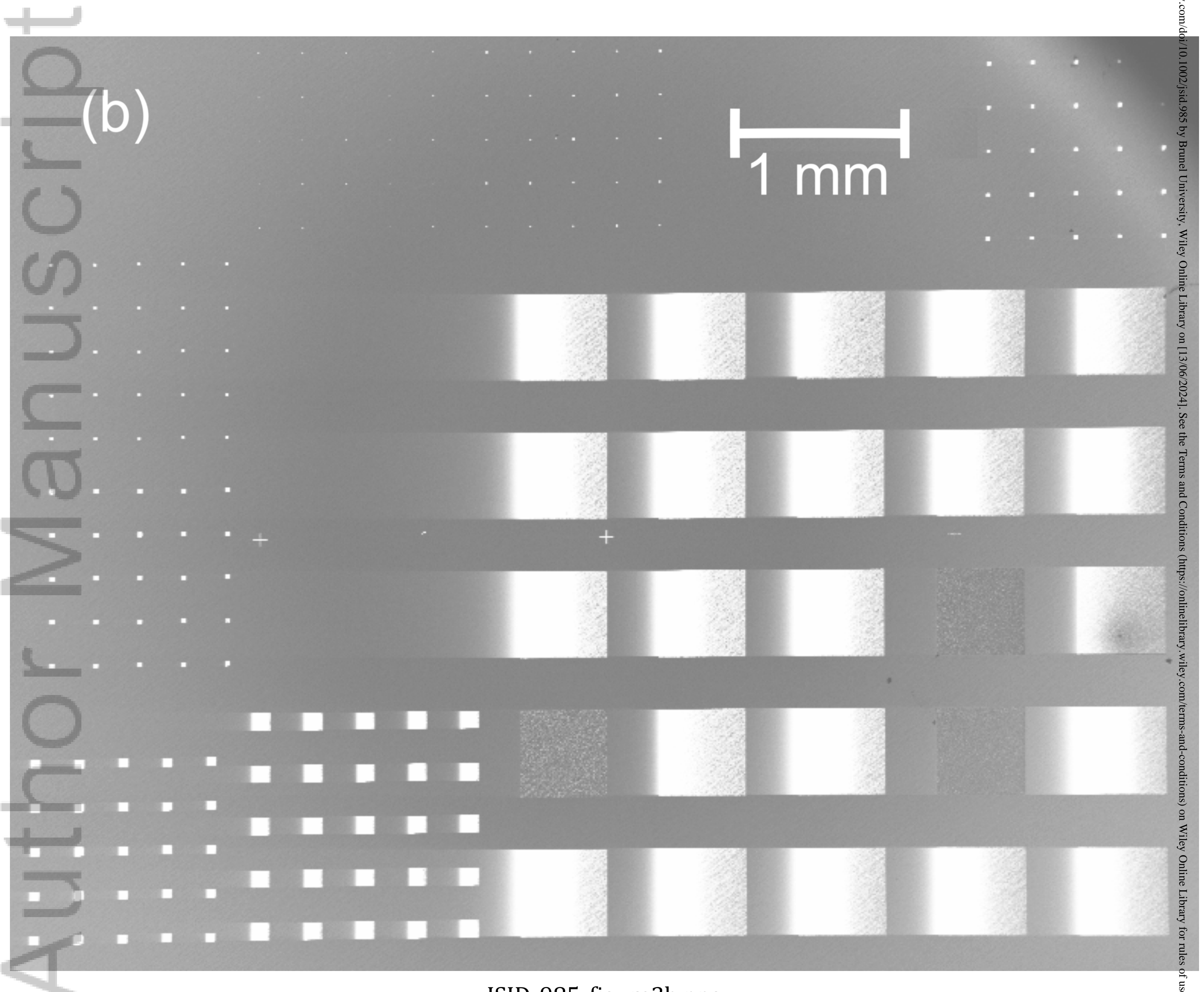

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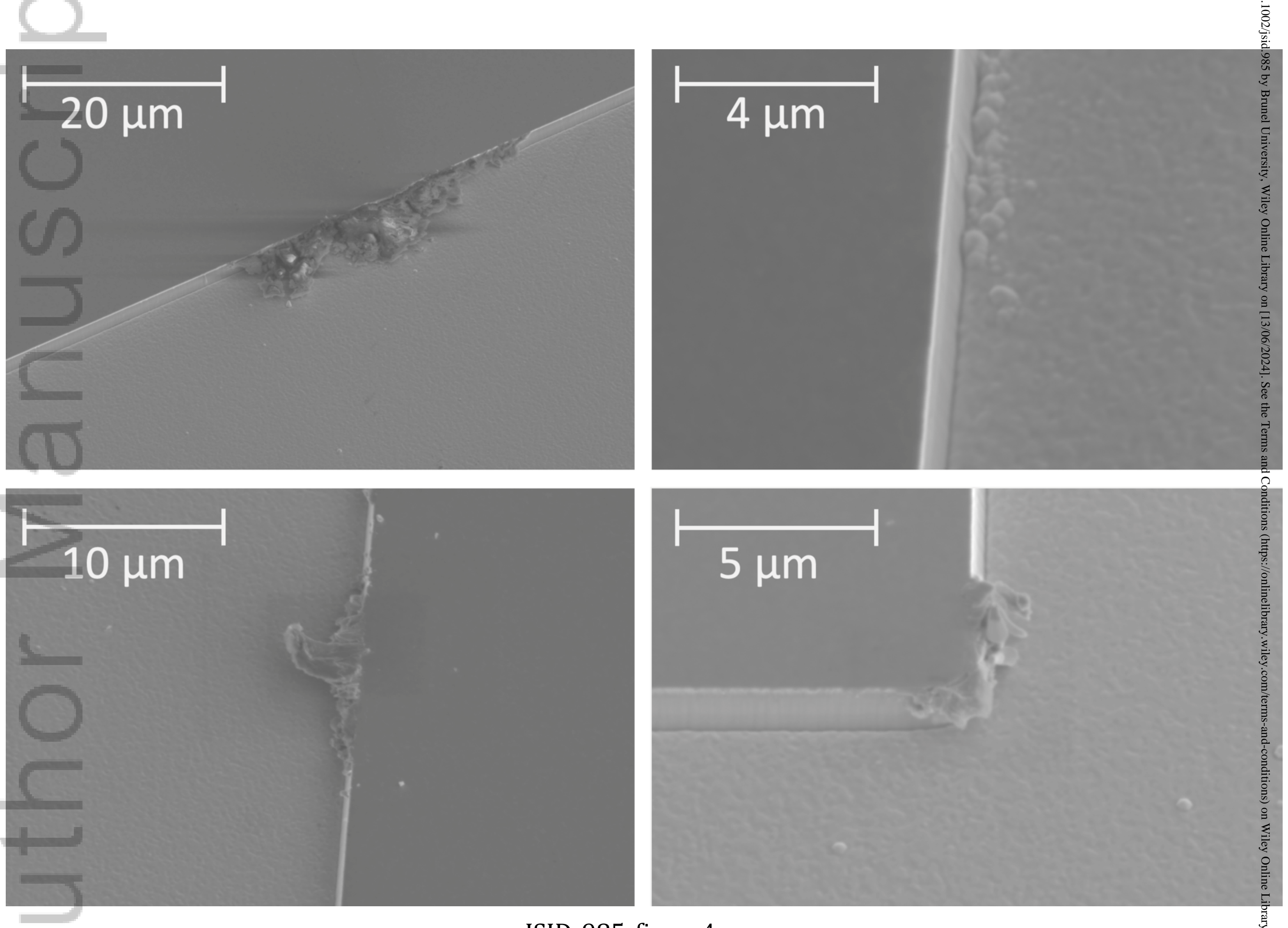

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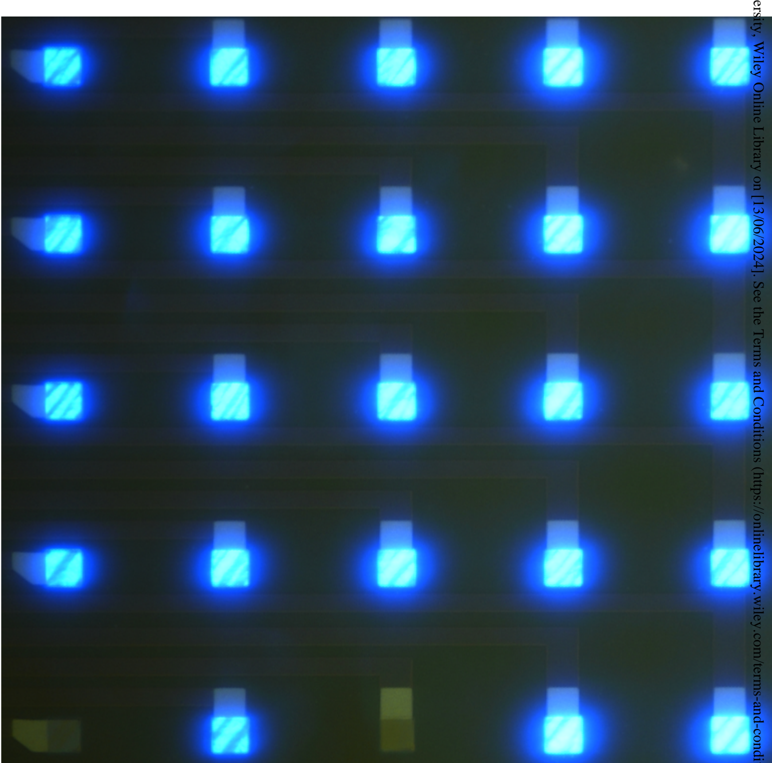

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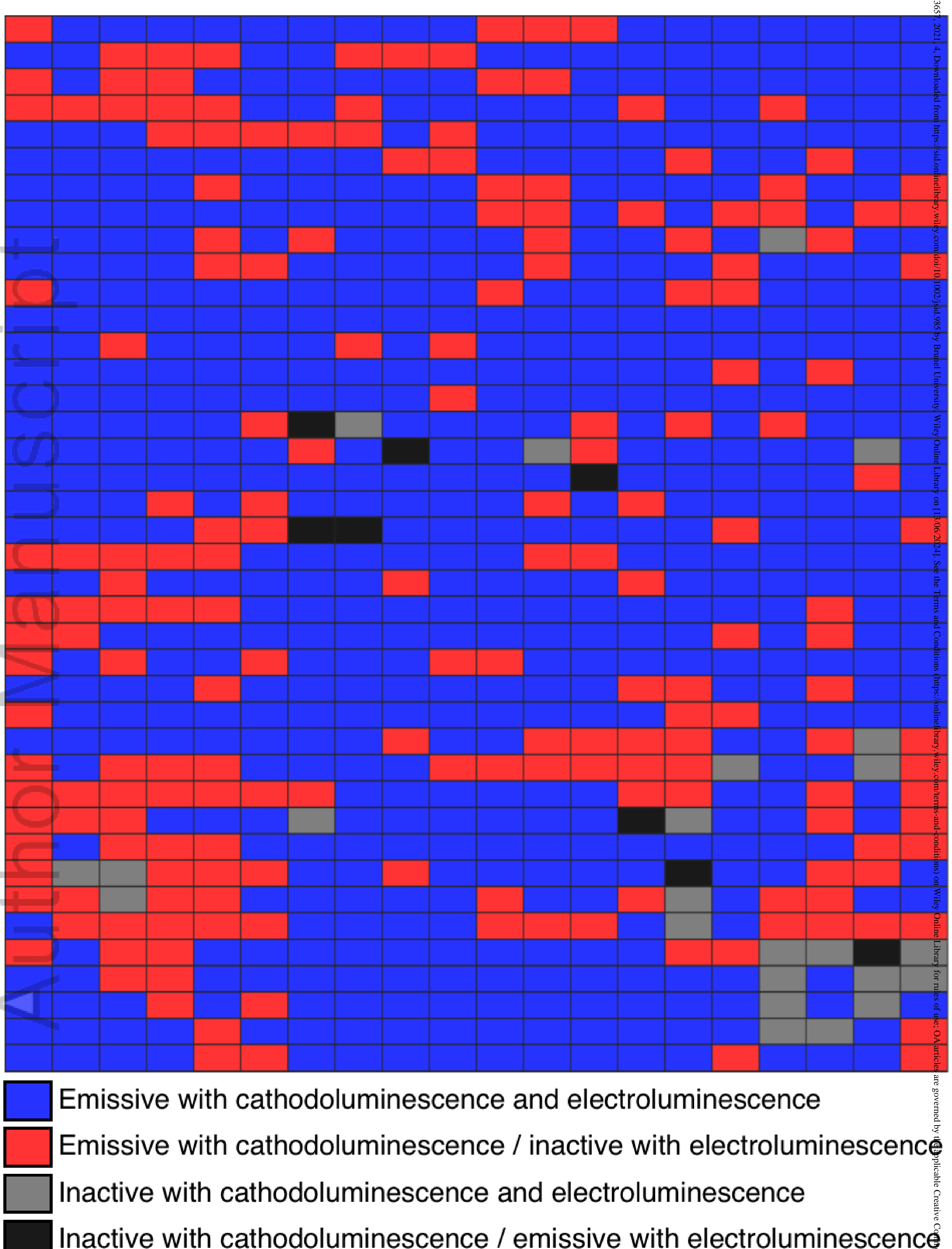

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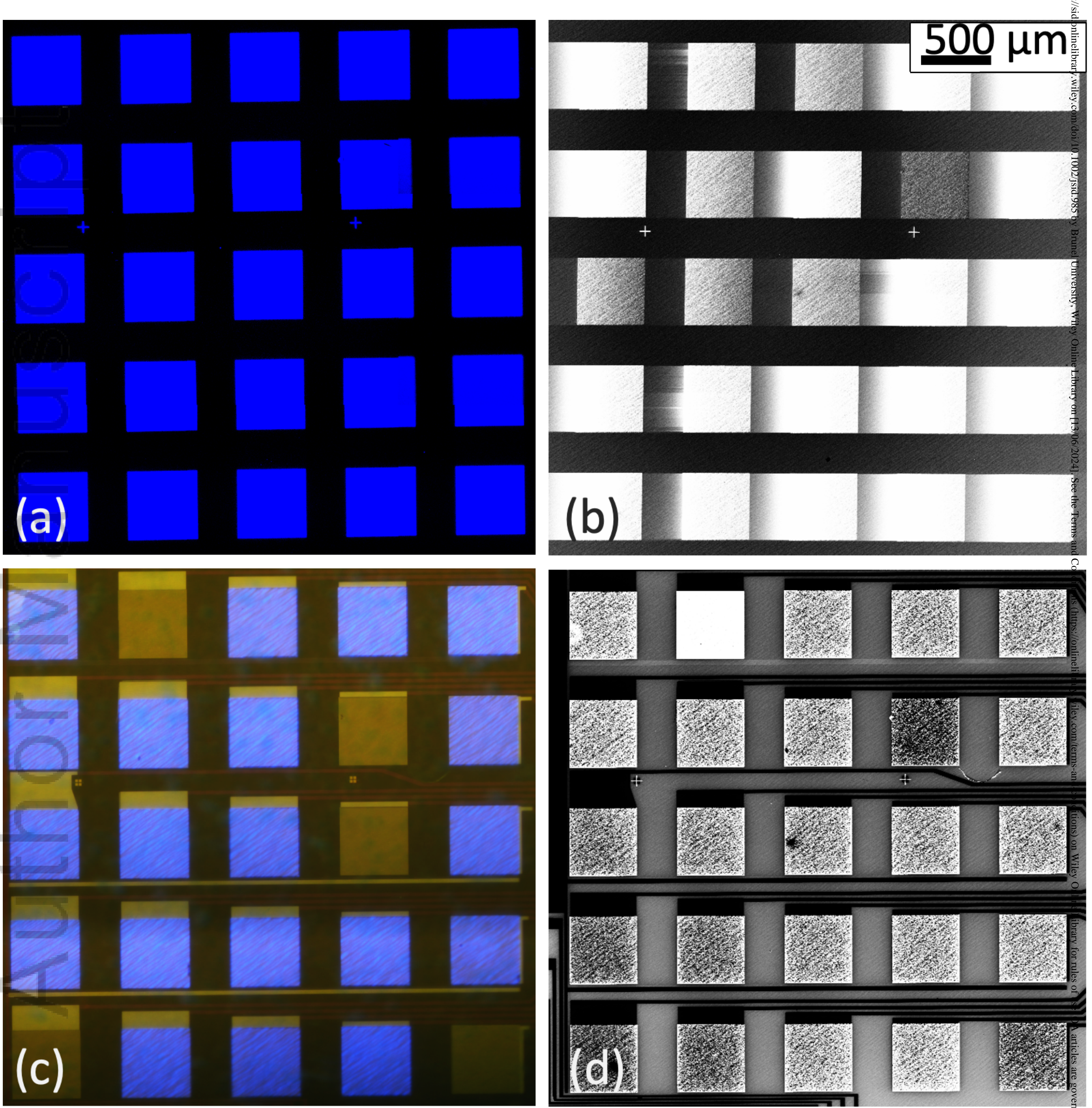

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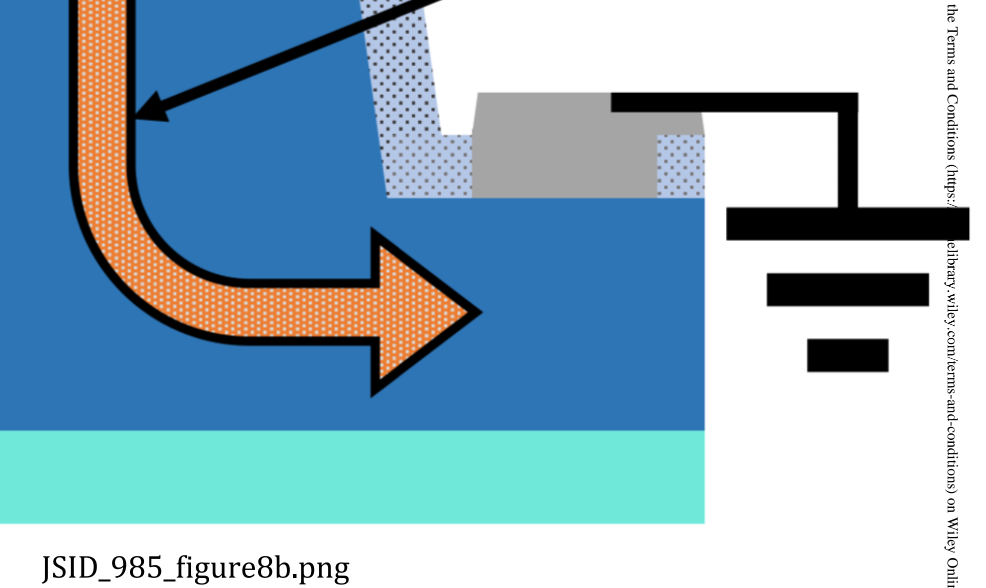

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