MicroLED/LED Electro-optical Integration Techniques for Non-Display Applications

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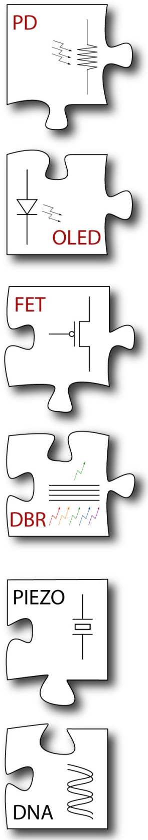
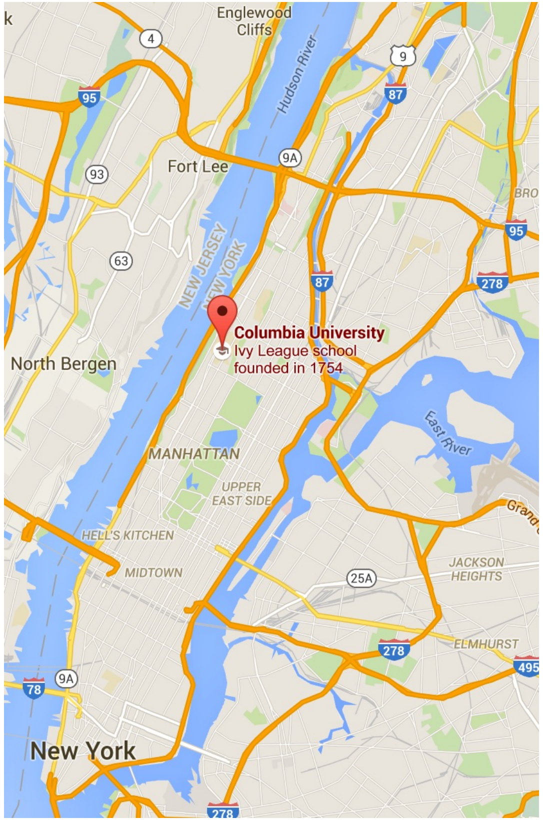
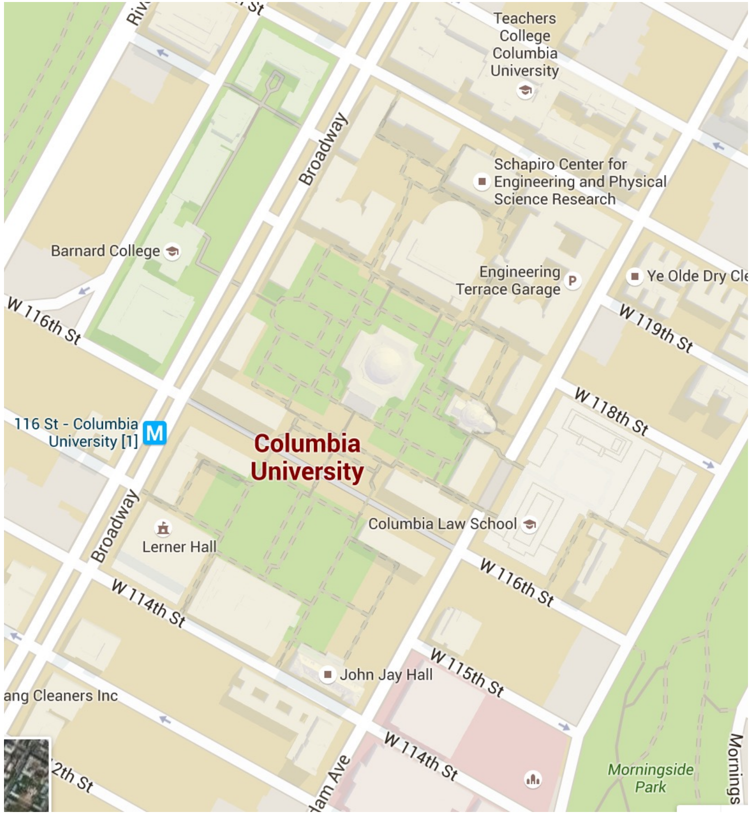


Columbia University…where are we?

Columbia Laboratory for Unconventional Electronics CLUE





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- Columbia University's EE department

  30 faculty, and (normally) ~100 undergrads, ~160 Ph.D. students, ~350 MS students

  This year we are just shy of 900 students

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LED displays represent the brightest, most efficient structured light sources possible with any known technology

- 20-50M nits (visible)
- High power conversion efficiency
- Emissive display
- No filters or polarization management needed (2-5x)

Great (at least on paper) for displays, we should also consider them for non-display applications

Just how much luminance?

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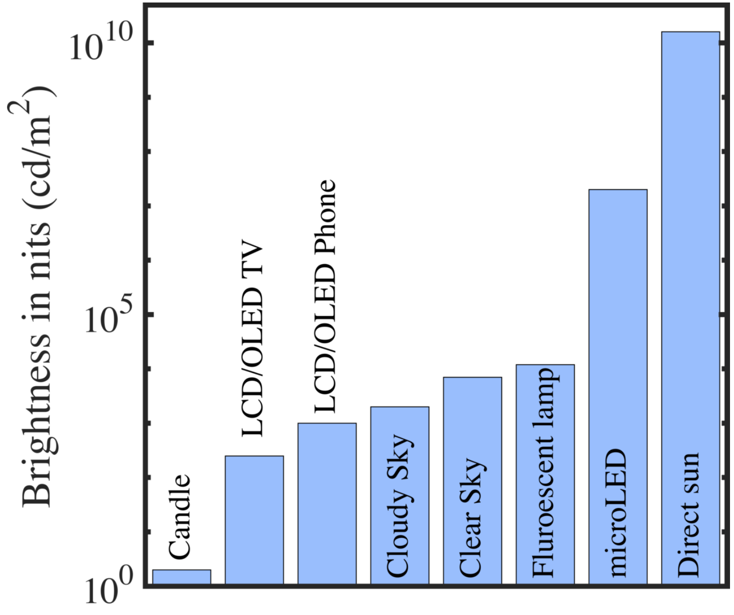

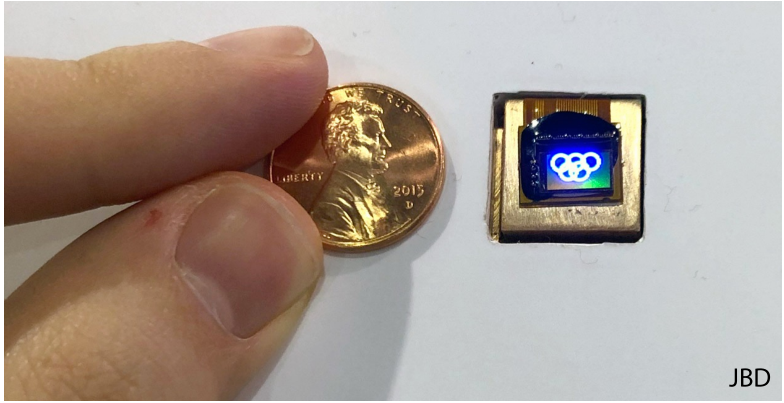

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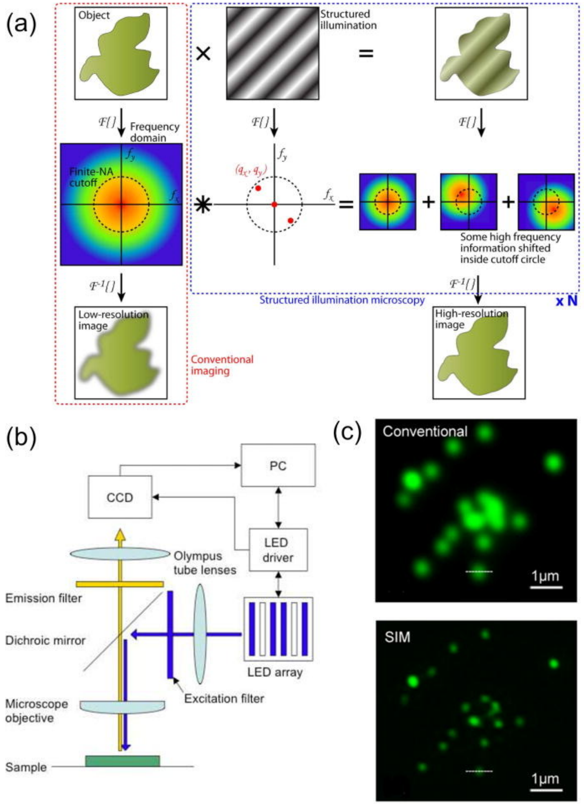
What can we do with them?

- Displays
  - DV
  - Indirect view

Behrman K, Kymissis I. Micro light-emitting diodes. Nature Electronics. 2022 Sep 22:1-0.

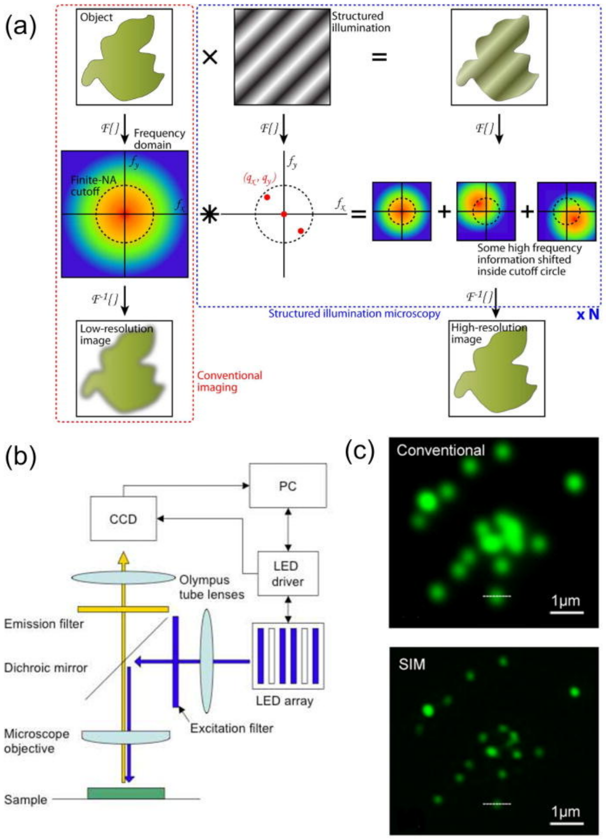
- Non-display

Kumar V, Kymissis I. MicroLED/LED electro-optical integration techniques for non-display applications. Applied Physics Reviews. 2023 Jun 1;10(2).



A few (non-display) applications for microLEDs

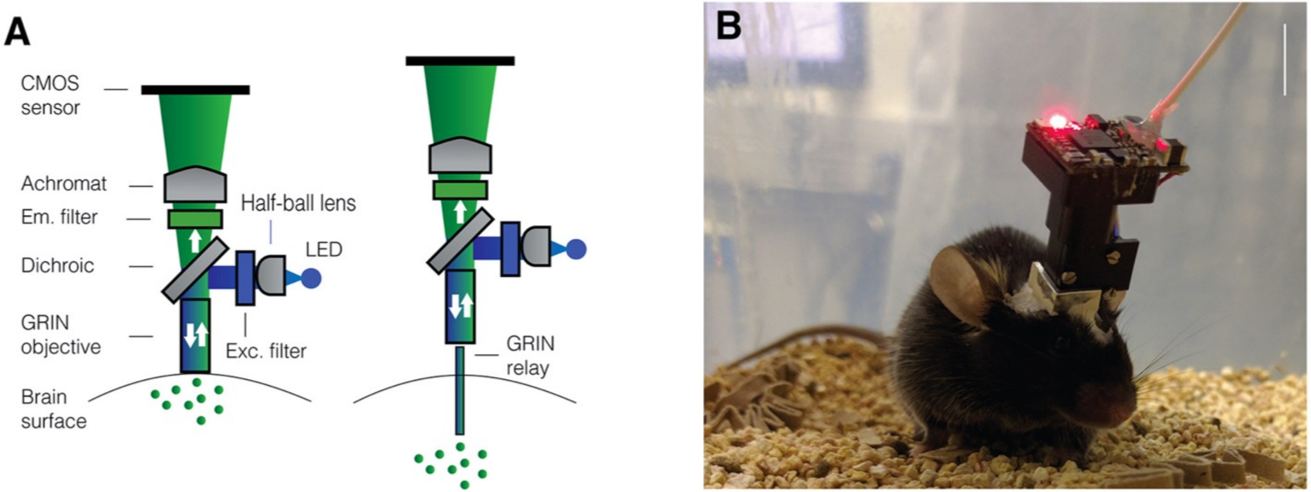
Superresolution microscopy using structured light



- Structured light allows for significant improvement in the images captured by optical systems
- Even a simple multiple exposure pattern can be used (e.g. alternating bars)

(a) McLeod and Ozcan, Rep. Prog. Phys. 79, 076001 (2016)
(b) Poher et al., Optics Express 15, 11196 (2007)
(c) Dan et al., Sci. Rep. 3, 1116 (2013)

Where might we do this (where LEDs offer an advantage)?



Aharoni, D. & Hoogland, T. M. Circuit Investigations With Open-Source Miniaturized Microscopes: Past, Present and Future. *Front. Cell. Neurosci.* **13**, (2019).

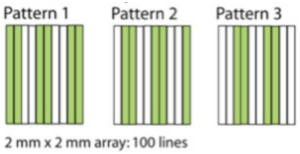
Collaboration with UC Boulder

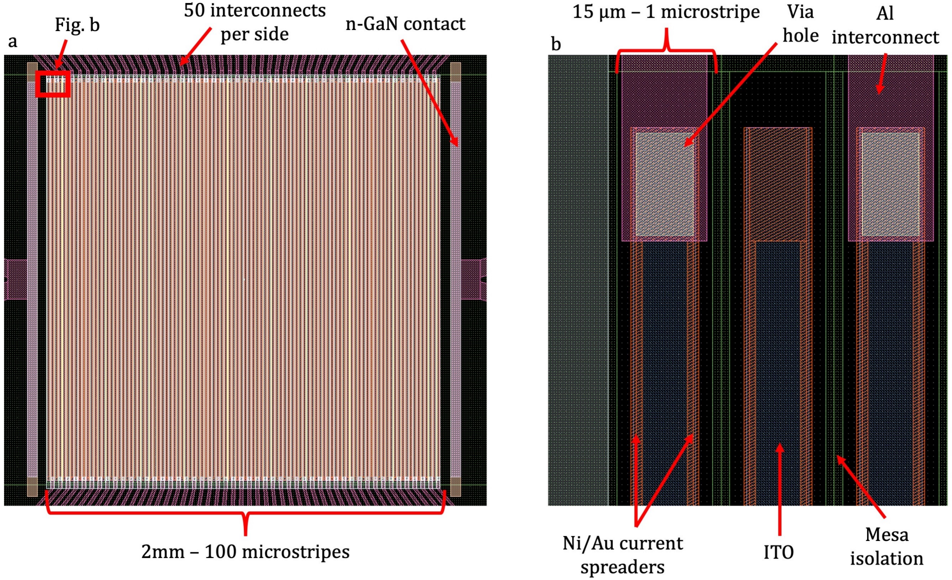
Layout for superresolution bar light source

2 mm x 15 µm emitters

100 microstripes

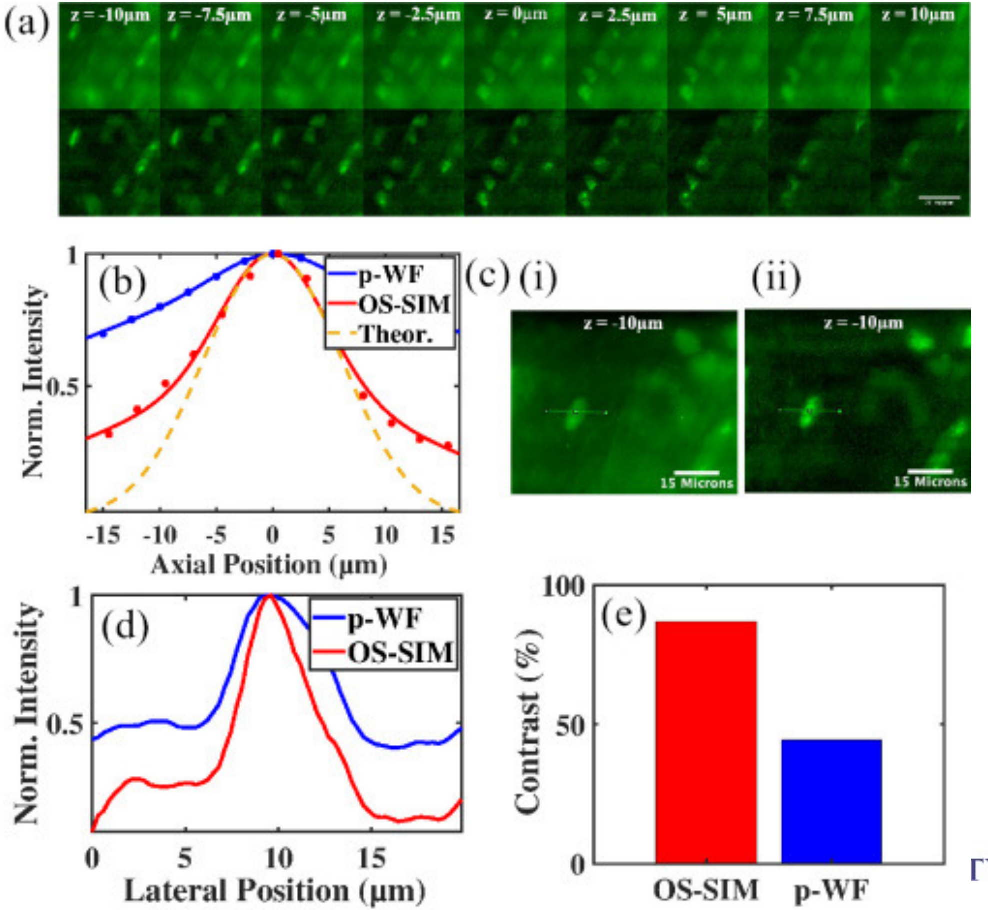
SIM lightsource





SRM using uLED

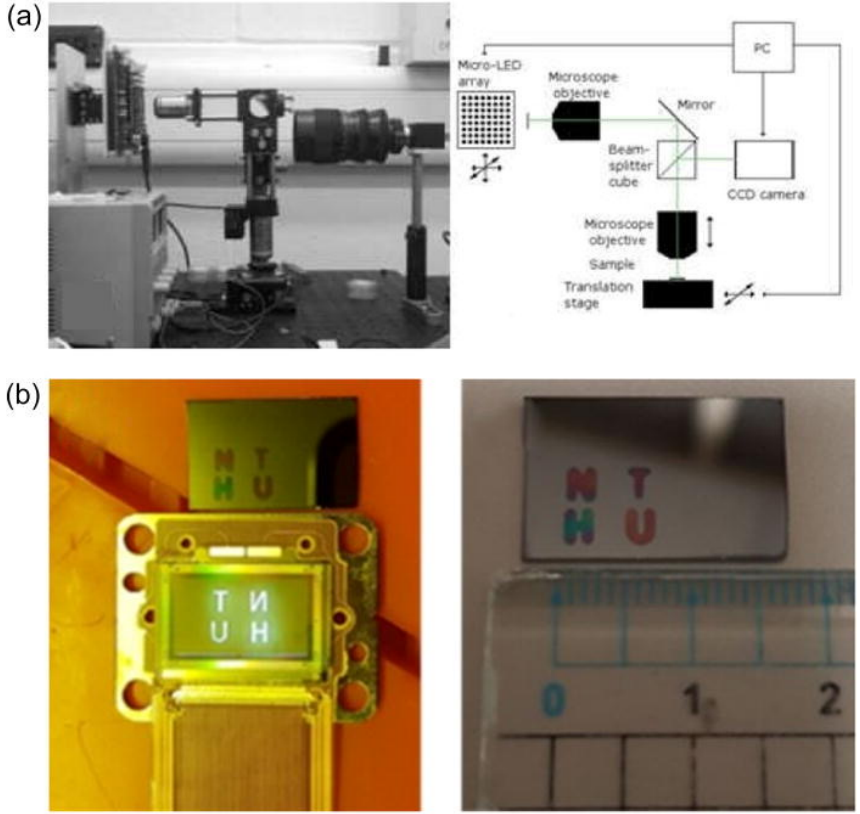
- With a few patterns SRM is possible in a lightweight/ portable format



Kumar V, Behrman K, Speed F, Saladrigas CA, Supekar O, Huang Z, Bright VM, Welle CG, Restrepo D, Gopinath JT, Gibson EA. MicroLED light source for optical sectioning structured illumination microscopy. Optics Express. 2023 May 8;31(10):16709-18.

Photolithography

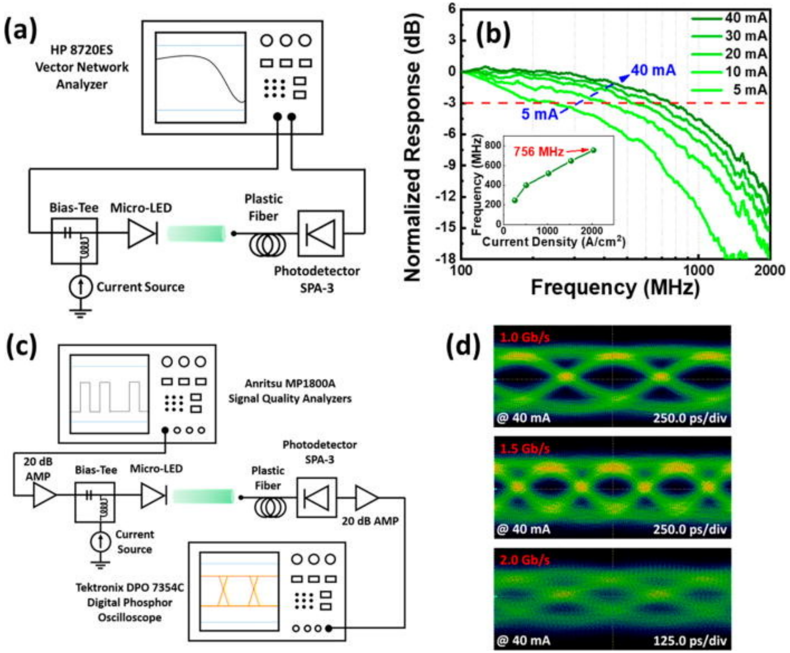
- The high intensity allows for structured maskless exposure
- Shorter wavelengths are available than ever
- The high speed also (possibly) allows for better control



Elfström et al., Opt. Express 17(26), 23522–23529 (2009).<

Visible light communication

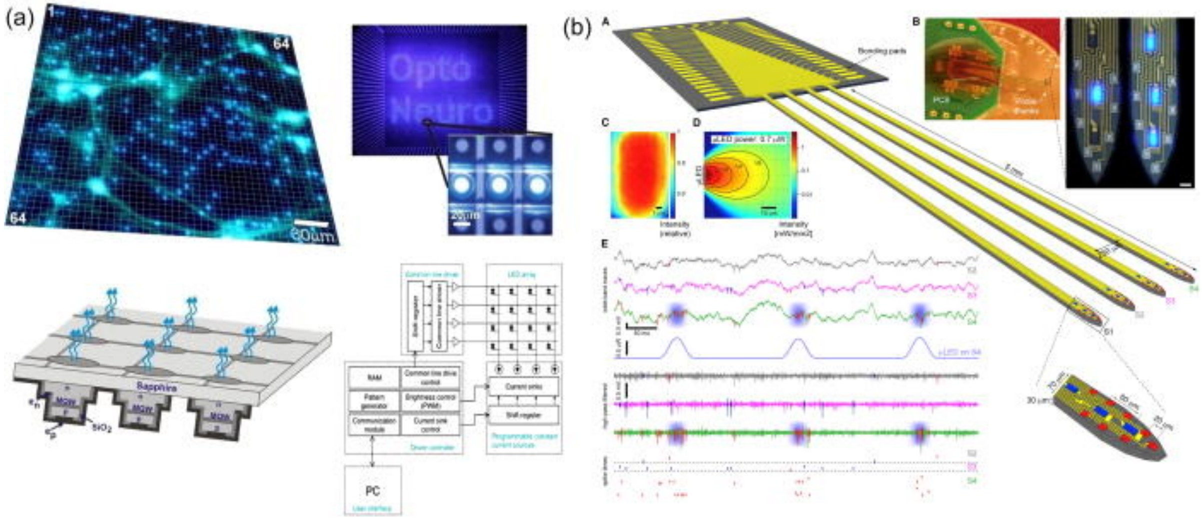
- LEDs allow for straightforward integration (esp for free-space)
- MicroLEDs permit faster switching than "bulk" LED structures



Chen et al., ACS Photonics 7, 2228 (2020).

Photostimulation

- Optogenetics + other photostimulation approaches

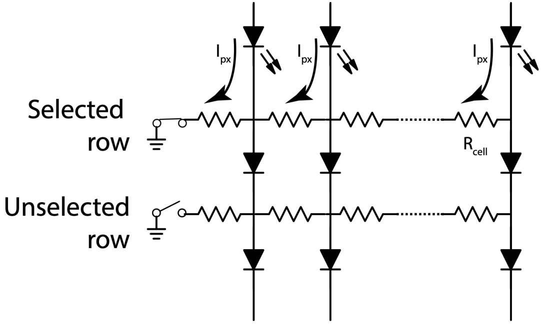


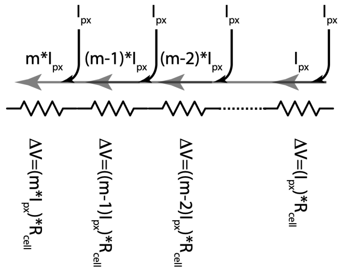
(a) Grossman et al., J. Neural Eng.7, 16004(2010)
(b) Wu et al., Neuron 88, 1136 (2015).

What are some of the material/format issues for non-display microLEDs?

MicroLEDs (all LEDs) need a backplane to have reasonable resolution

- It's well established that a backplane is needed to drive microLEDs at anywhere close to peak efficiency/luminance/duty cycle/etc.





$$\Delta V_{max} = \sum_{x=0}^{m} x * I_{px} * R_{cell}$$

$$\Delta V_{max} = \frac{m(1+m)}{2} * I_{px} * R_{cell}$$

$$\Delta V_{max} \approx \frac{m^2}{2} * I_{px} * R_{cell}$$

An active matrix is complicated!

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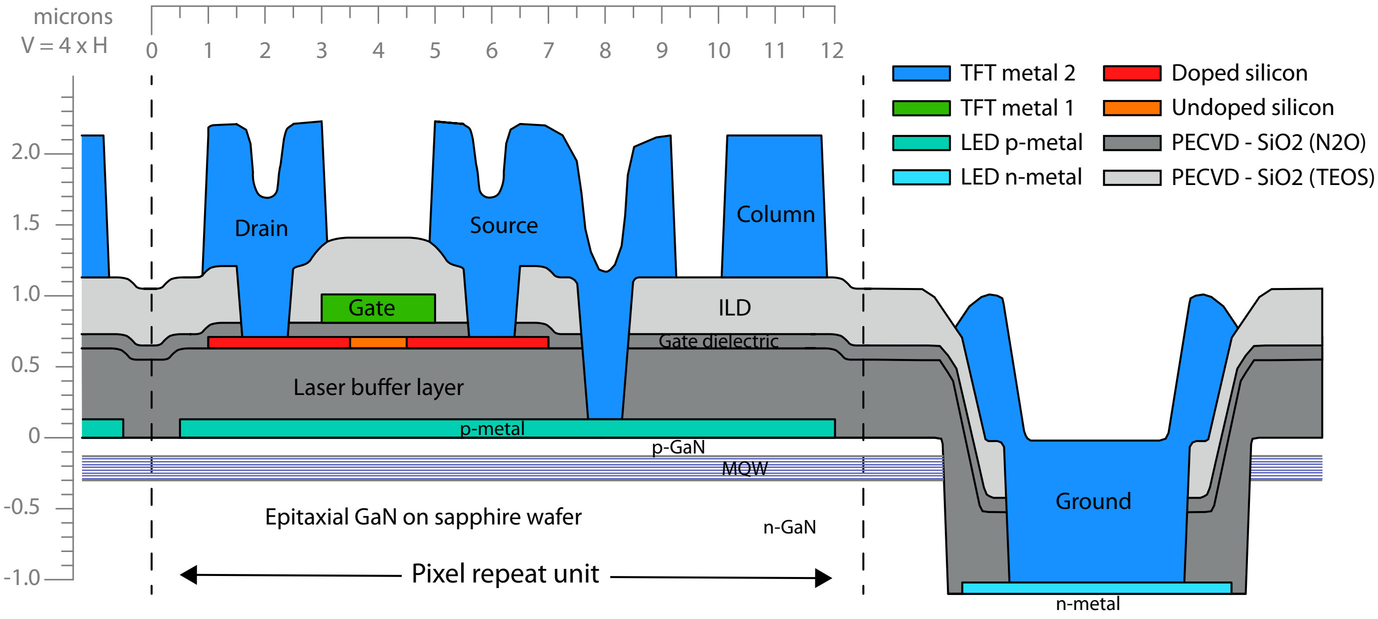

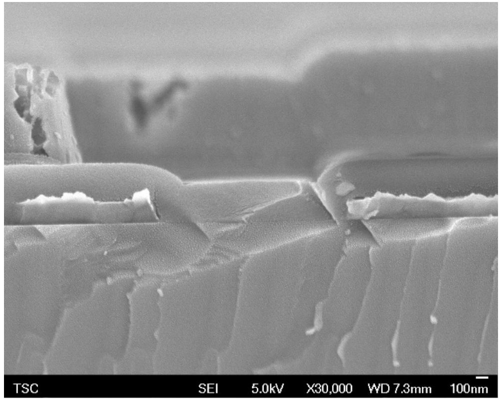

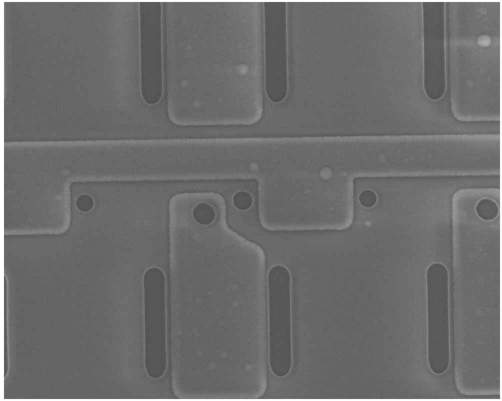

Tull BR, Twu N, Hsu YJ, Leblebici S, Kymissis I, Lee VW. 19-1 Micro-LED Microdisplays by Integration of III-V LEDs with Silicon Thin Film Transistors. SID symposium digest of technical papers 2017 May (Vol. 48, No. 1, pp. 246-248).

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Usually (!) we can get away with a passive matrix

- For low resolution… more than adequate
- Requires some consideration, since we have to trench the LEDs (creating mesas)

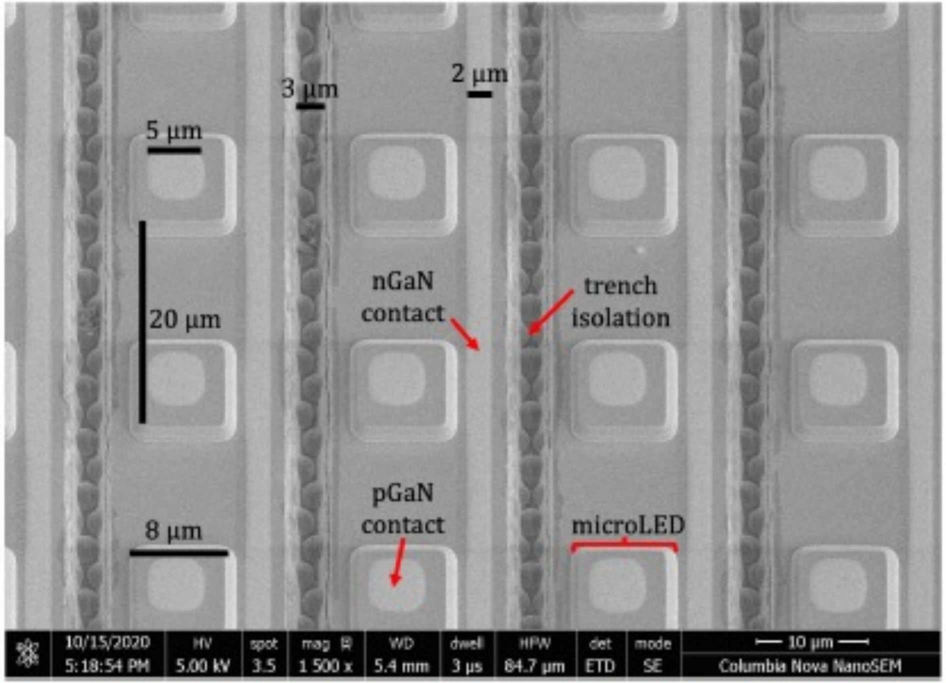


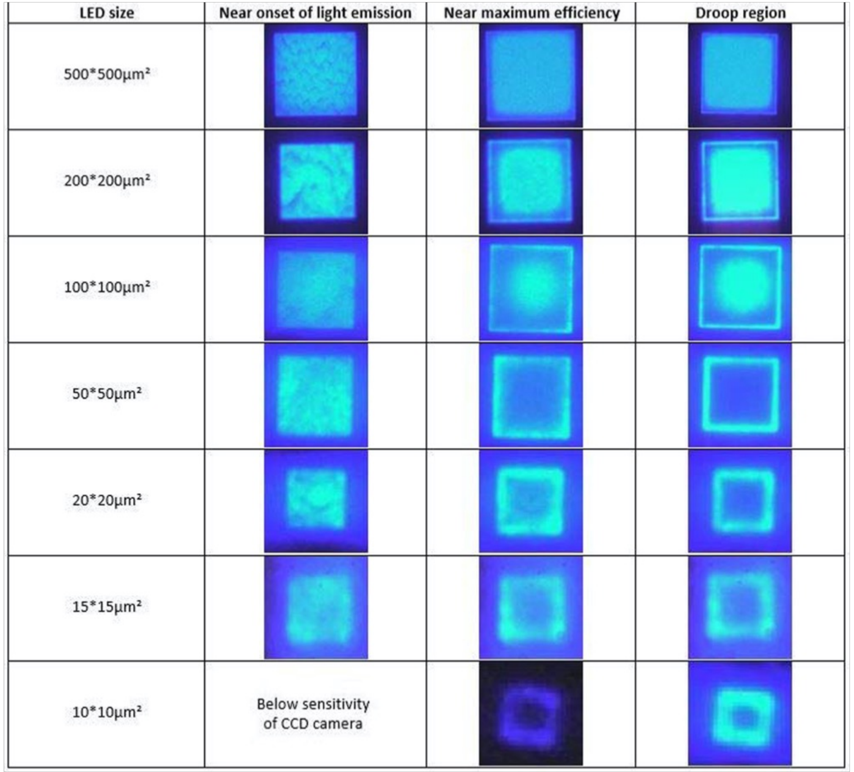
Figure 4.12: 40° tilted SEM image of the same display from Fig. 4.11 detailing the design dimensions and feature identification.

Beherman, thesis

Isolation/Efficiency/Current Density

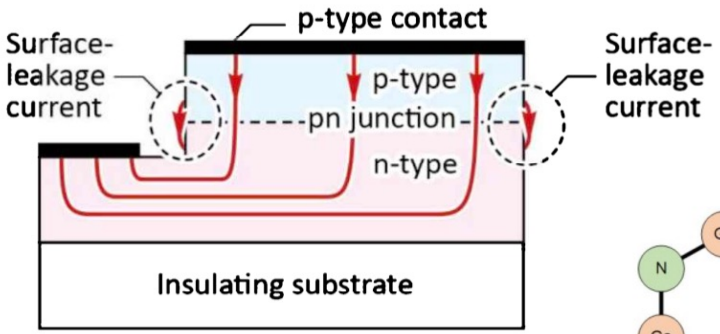
How small is too small?

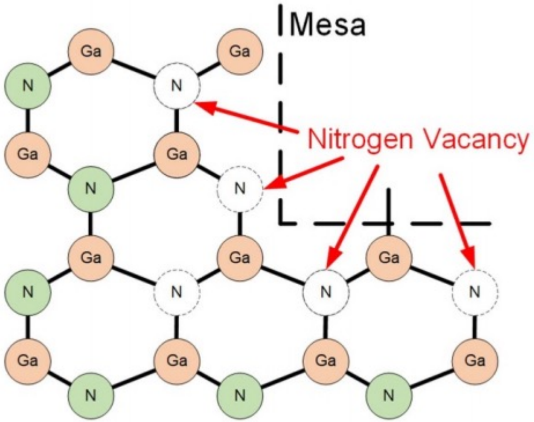
- There is some sidewall recombination that is seen in both monolithic and chiplet devices
- There is illumination inhomogeneity associated with damage, waveguiding, and sidewall recombination

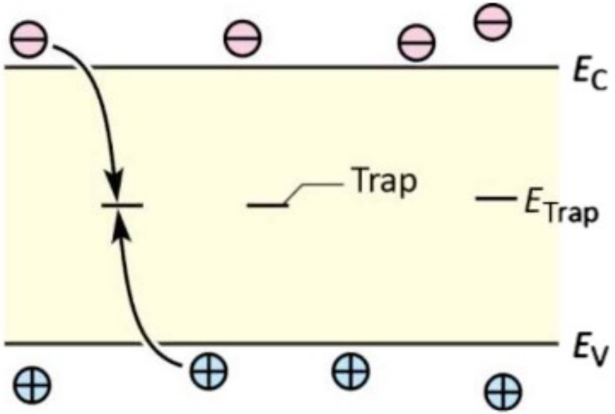


https://doi.org/10.1016/j.jcrysgro.2004.04.085

Sidewall recombination is one challenge





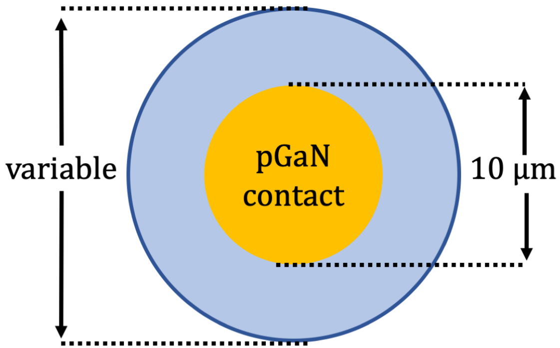


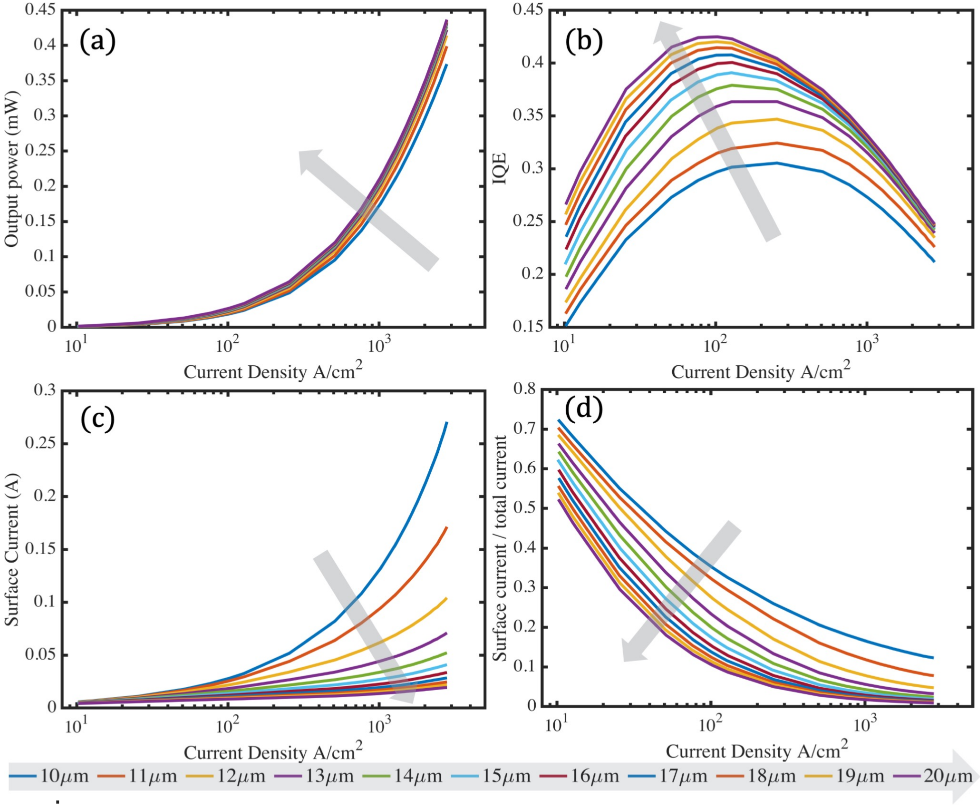
Schubert, E. F. *Light-Emitting Diodes*. (Cambridge University Press, 2006).

Sun, Y. *et al.* High-power and broadband microwave detection with a quasi-vertical GaN Schottky barrier diode by novel post-mesa nitridation. *Semicond. Sci. Technol.* **36**, 03LT01 (2021).

Current density is another

Current density calculated by pGaN contact area for consistency (modeled)





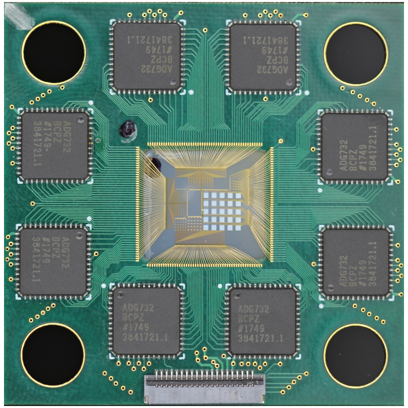
Behrman K, Kymissis I. Enhanced microLED efficiency via strategic pGaN contact geometries. Optics Express. 2021 May 10;29(10):14841-52.

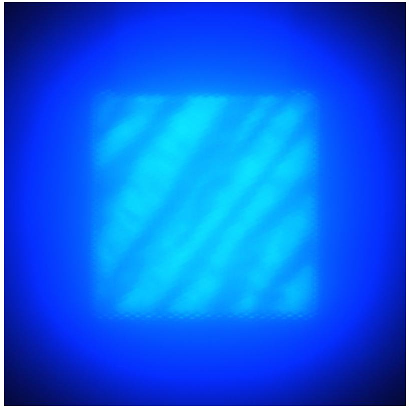
Yield is a third …

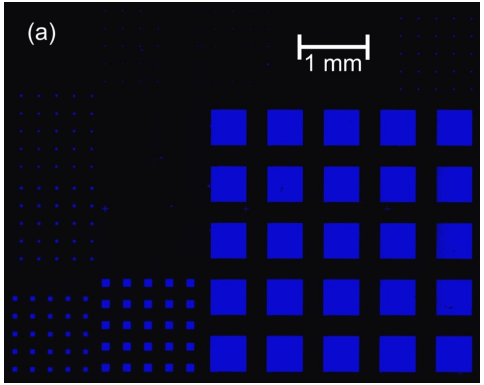
Photoluminescence

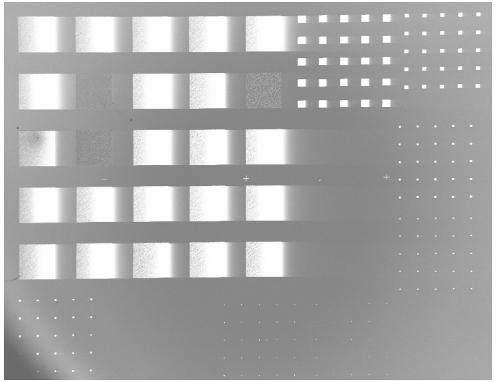
Cathodoluminescence

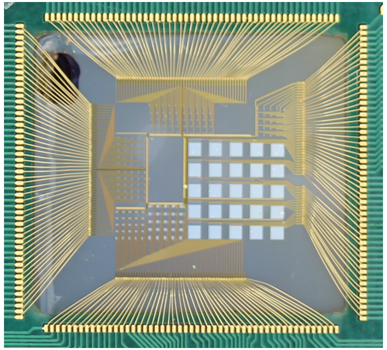
Electroluminescence

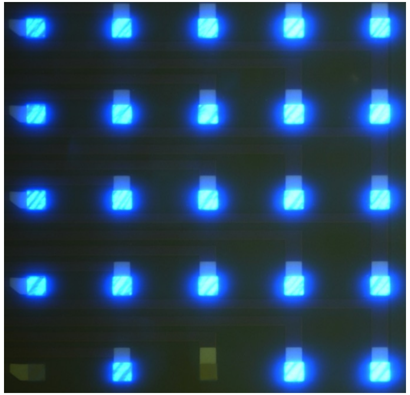








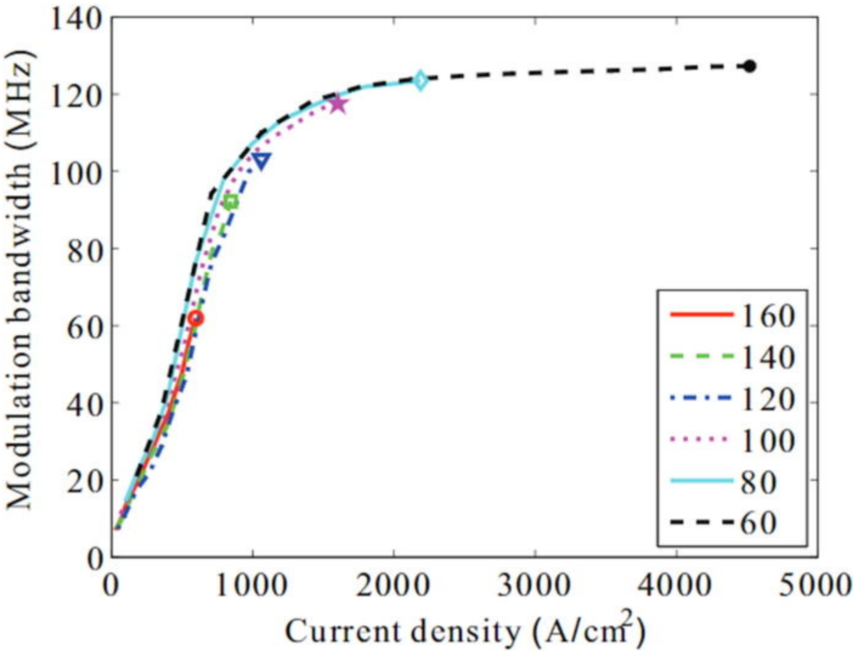




Behrman, K., Fouilloux, J., Ireland, T., Fern, G. R., Silver, J., & Kymissis, I. (2021). Early defect identification for micro light-emitting diode displays via photoluminescent and cathodoluminescent imaging. Journal of the Society for Information Display, 29(4), 264-274.

Recombination is not always bad (?!)

- For OLC, recombination can help offer a greater apparent speed
- Smaller mesas as well as higher current density can deliver this

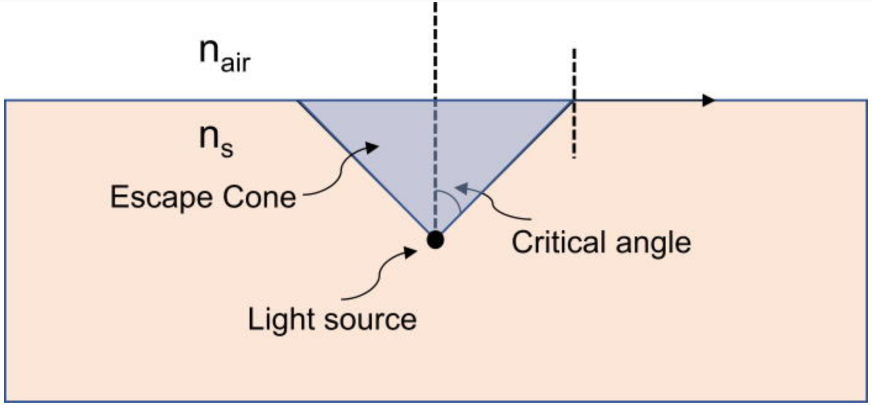


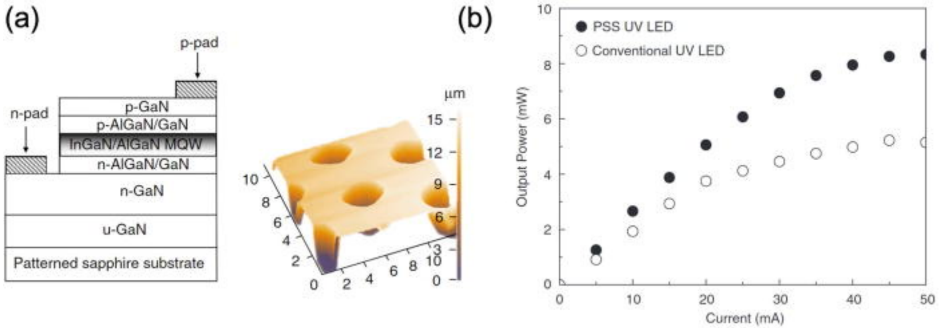
Huang et al., Phys. Status Solidi A 215, 1800484 (2018).<

Light extraction

Conventional extraction (e.g. LED lighting)

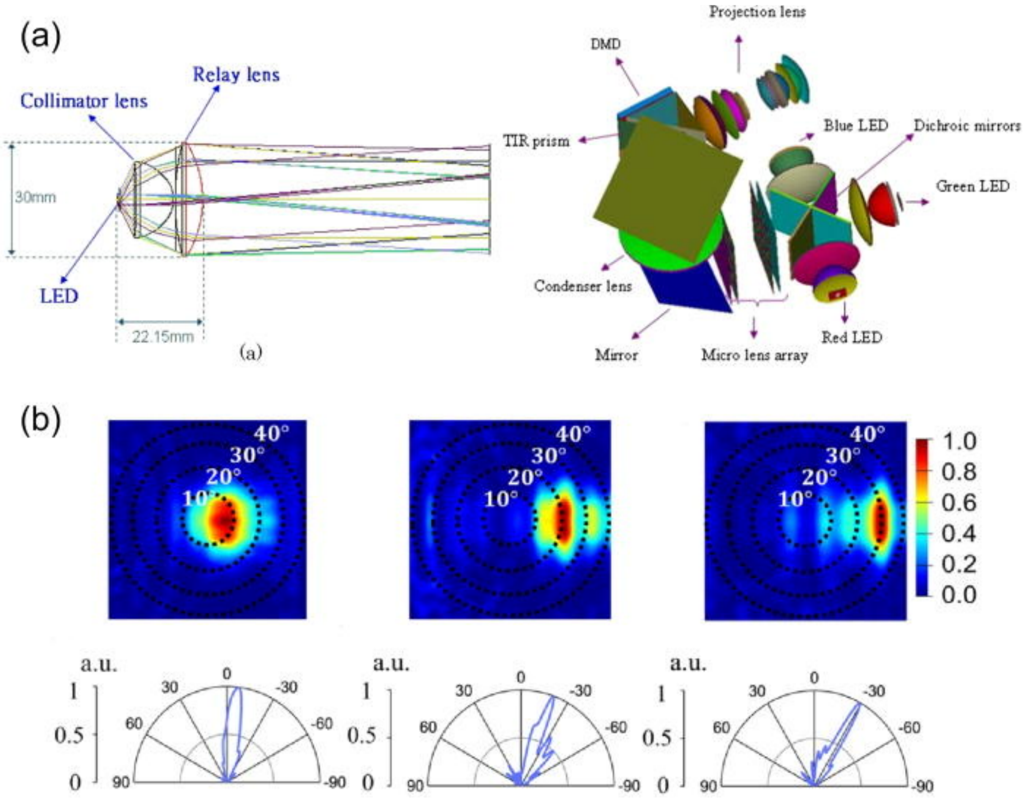
- PSS and roughening can extract the light well
- This occurs through scattering, and loses the positional information usually required





Horng et al., J. Crystal Growth 298, 219 (2007

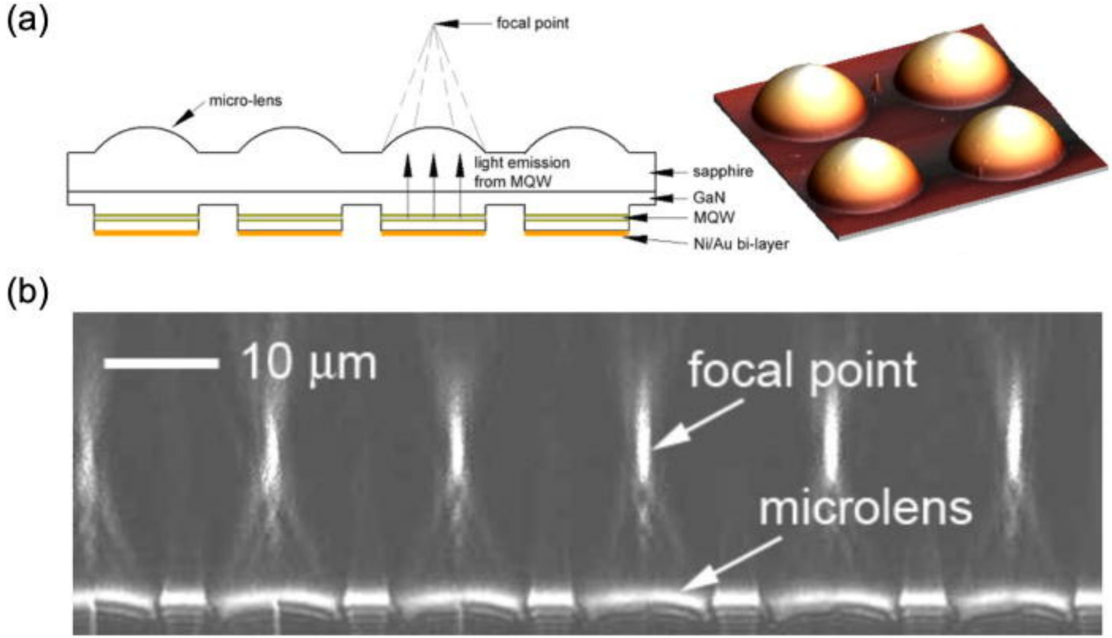
- Near-field optics allow for better coupling to optical system without losing the spatial structure



Huang et al., Opt. Lett. 46, 3476 (2021).

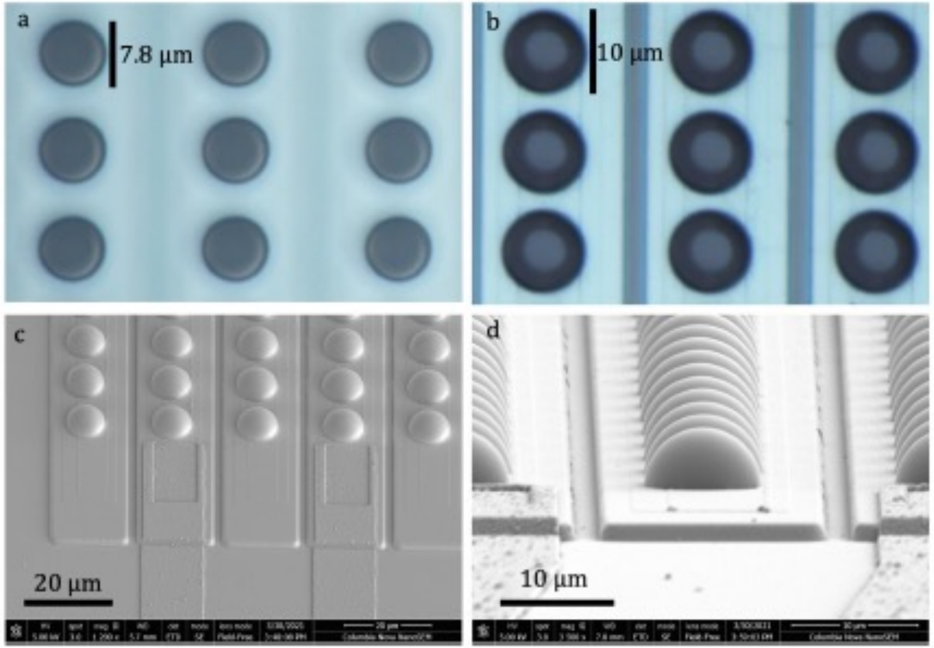
Microlenses

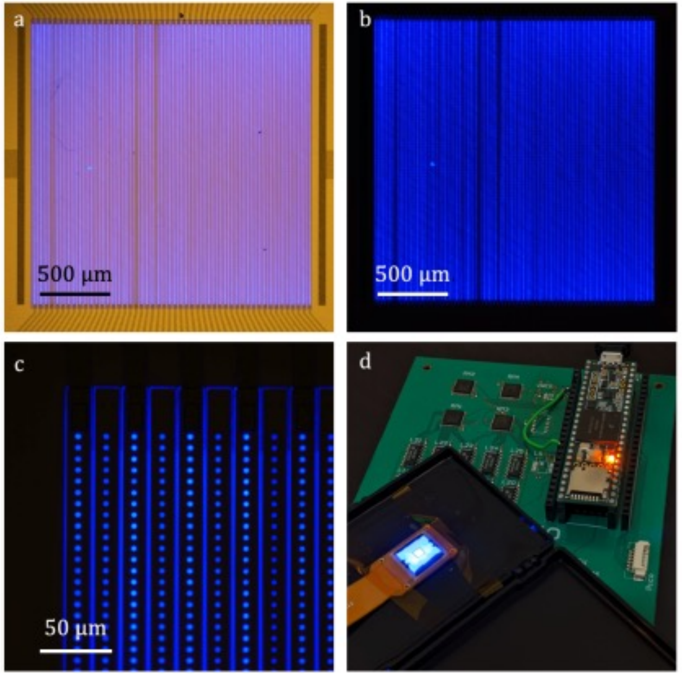
- Many options for integration (e.g. reflow processes)



Choi et al., Phys. Status Solidi C 2, 2903 (2005).<

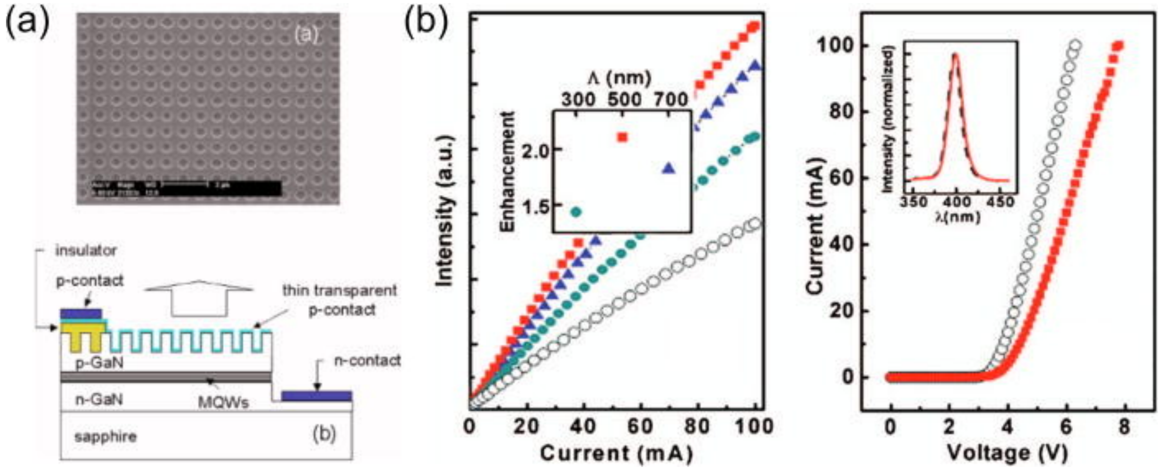
More microlenses + apertures





Beherman

- Flat optics (e.g. photonic crystals) can also deliver superior coupling without scattering

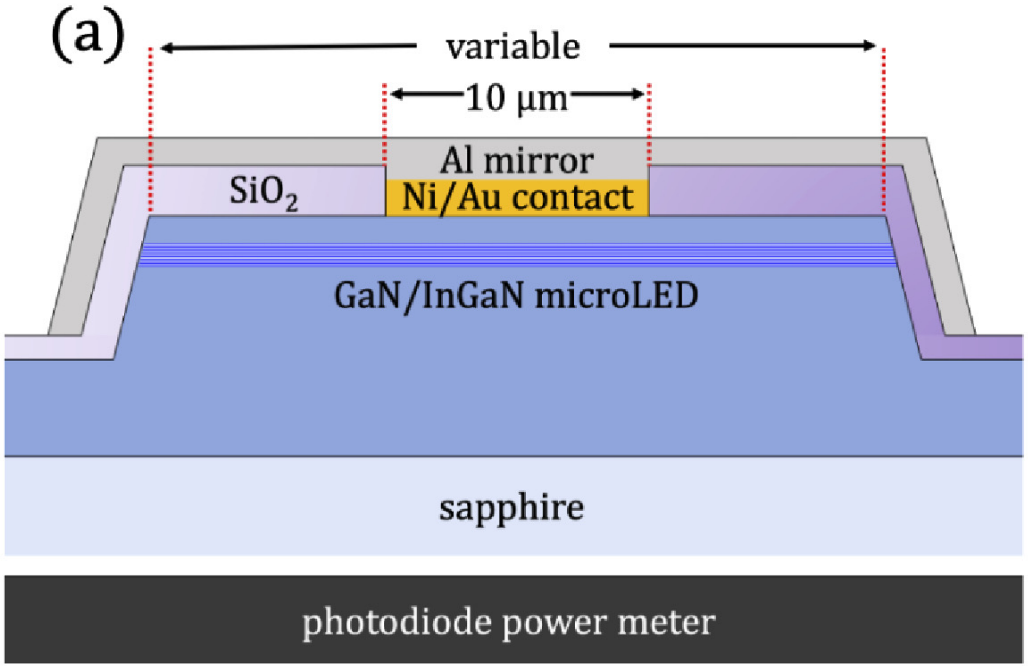


Kim et al., Appl. Phys. Lett. 87, 203508 (2005)

Wavelength control

To first order, most microLEDs are monochrome

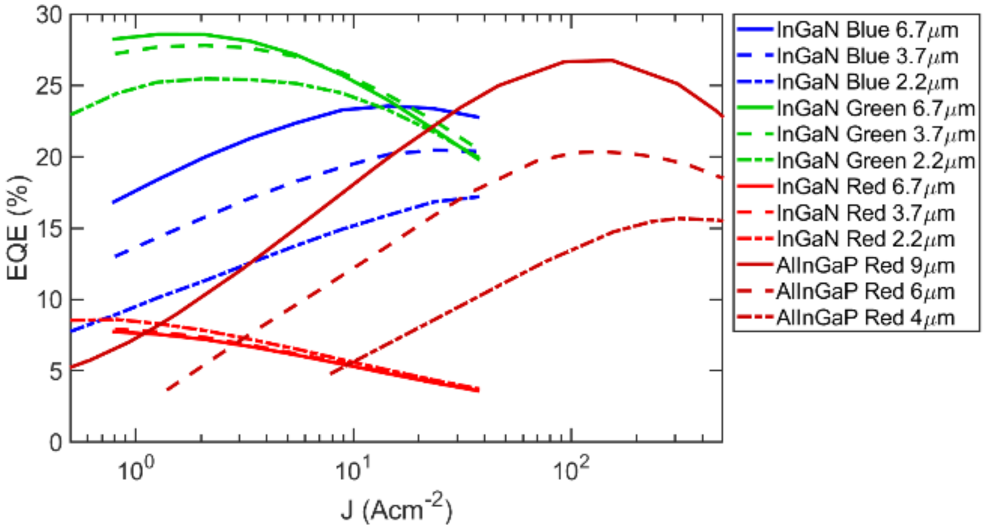
- You get what's cooked into the wafer, right?



Keith Behrman and Ioannis Kymissis, "Enhanced microLED efficiency via strategic pGaN contact geometries," Opt. Express 29, 14841-14852 (2021)

LEDs today are better than ever

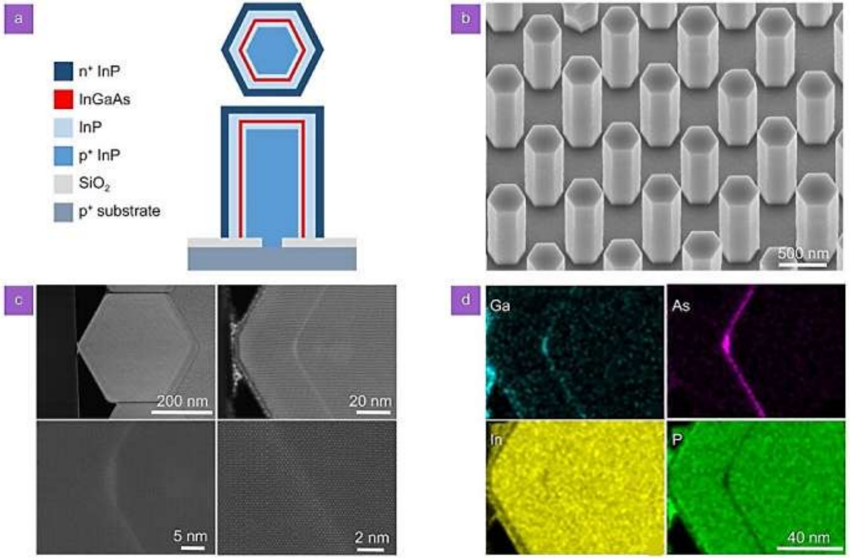
- New growth processes have overcome many of the challenges of the past



Moran, Brendan, et al. "29-5: Invited Paper: Progress in MicroLEDs: Materials, Device Performance, and Reliability." *SID Symposium Digest of Technical Papers*. Vol. 54. No. 1. 2023.

LEDs can also be grown and/or bonded together

- Most non-display applications need only one wavelength…but sometimes more than one is strategic (e.g. WDM)
- Bonding, nanowires, and downconversion can deliver this

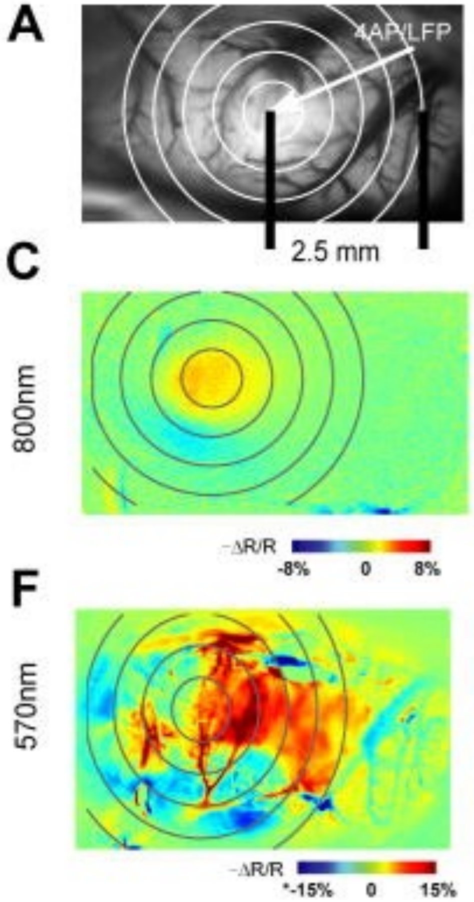


Fanlu Zhang et al, High-speed multiwavelength InGaAs/InP quantum well nanowire array micro-LEDs for next generation optical communications, *Opto-Electronic Science* (2023)

How about chiplets for non-display?

OLED+OPD=Brain Probe

- The brain is very tightly vasoregulated; IOS can measure activity
- In a seizure, there is a typical pattern of blood flow: deoxygenation, response, re-perfusion
- The spatial resolution of this response is better than 100um



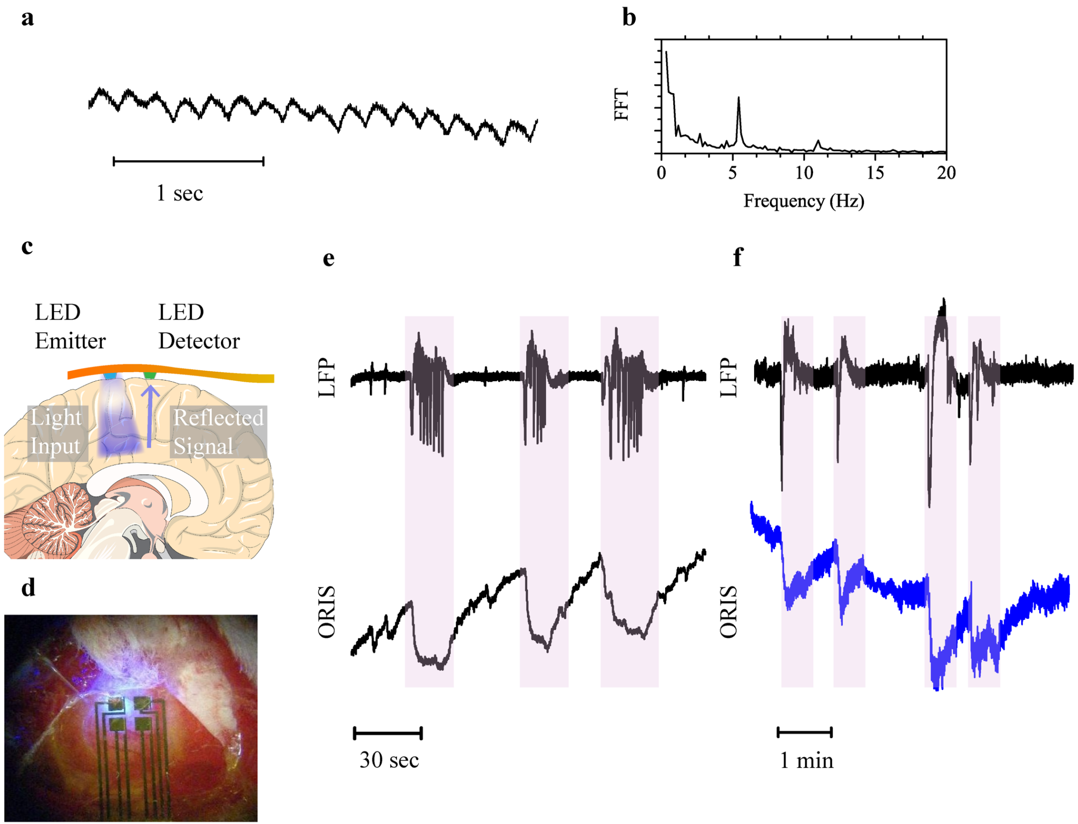
Collaboration with Hongtao Ma and Theodore Schwartz, Cornell Medical

An implantable monitor…

- Would allow for persistent monitoring
- Higher resolution than electrical measurement
- Could measure more than just spike activity

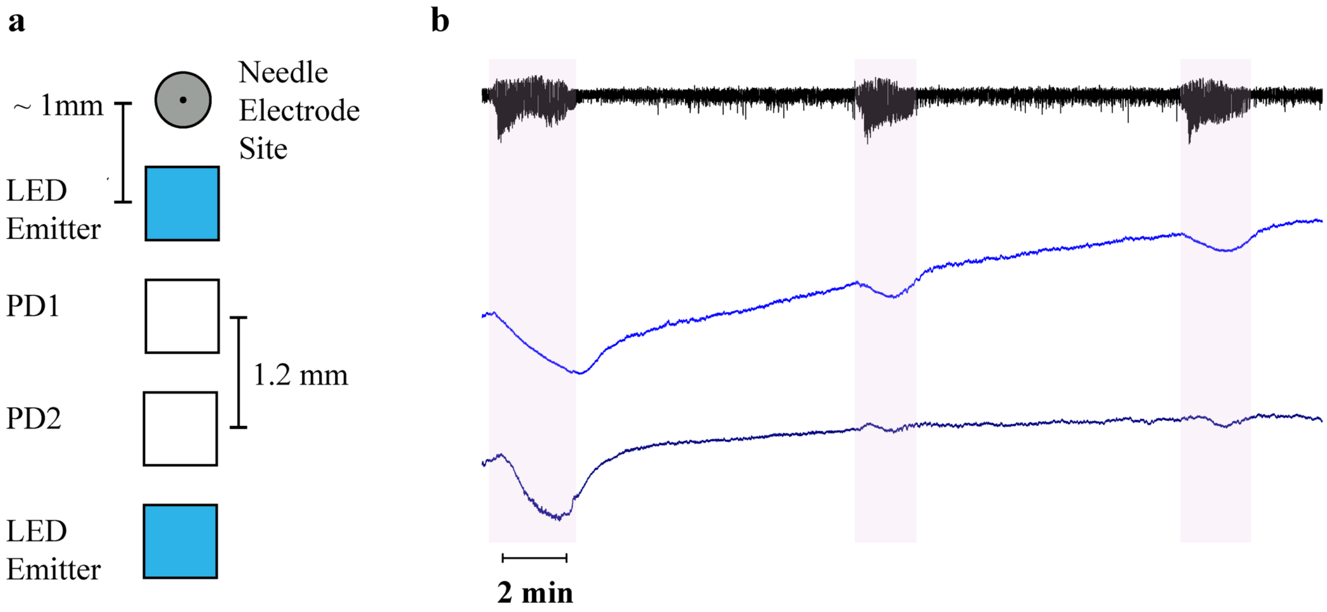
- But…needs to fit under the skull

Gen 3: uLED version

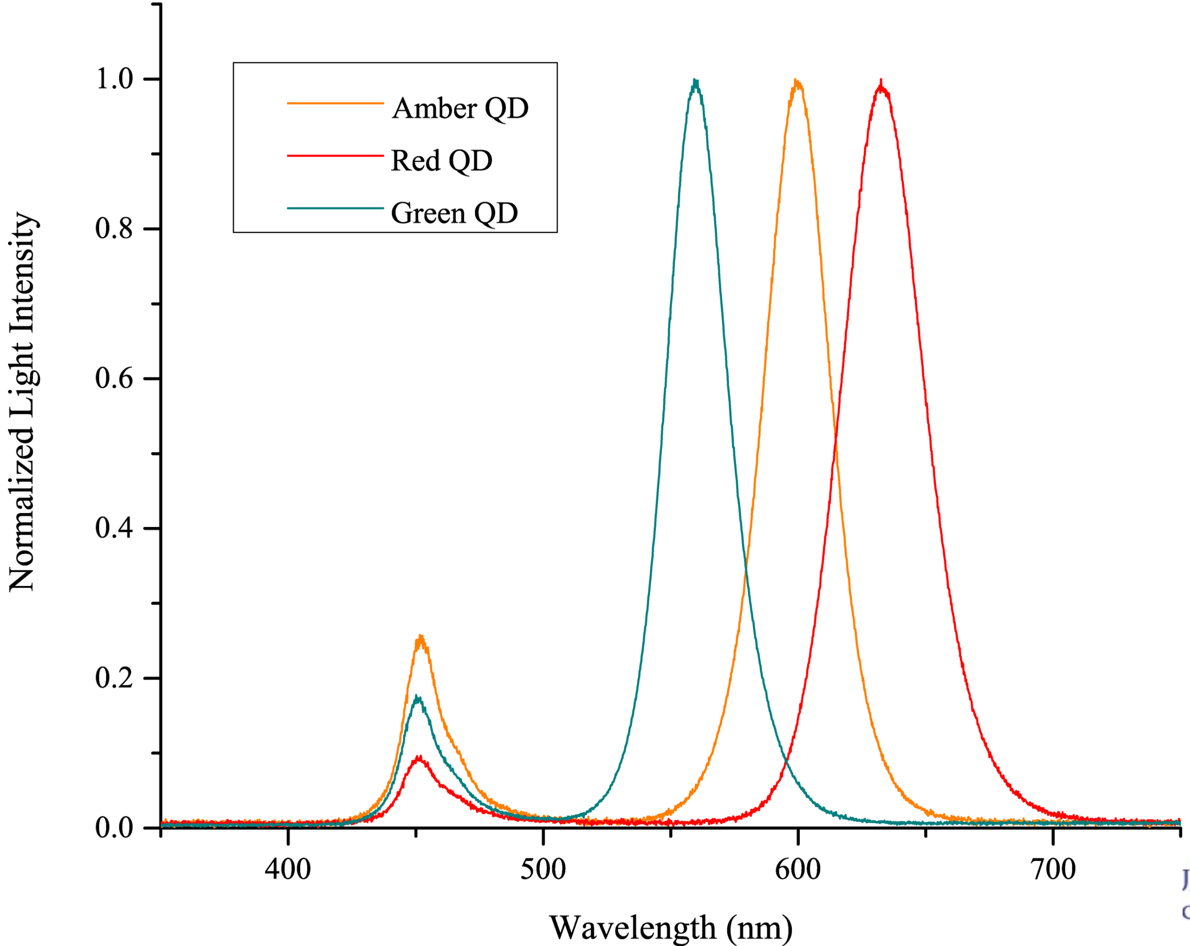


Choi C, Colón-Berríos AR, Hamachi LS, Owen JS, Schwartz TH, Ma H, Kymissis I. Localizing seizure activity in the brain using implantable micro-LEDs with quantum dot downconversion. Advanced Materials Technologies. 2018 Jun;3(6):1700366.

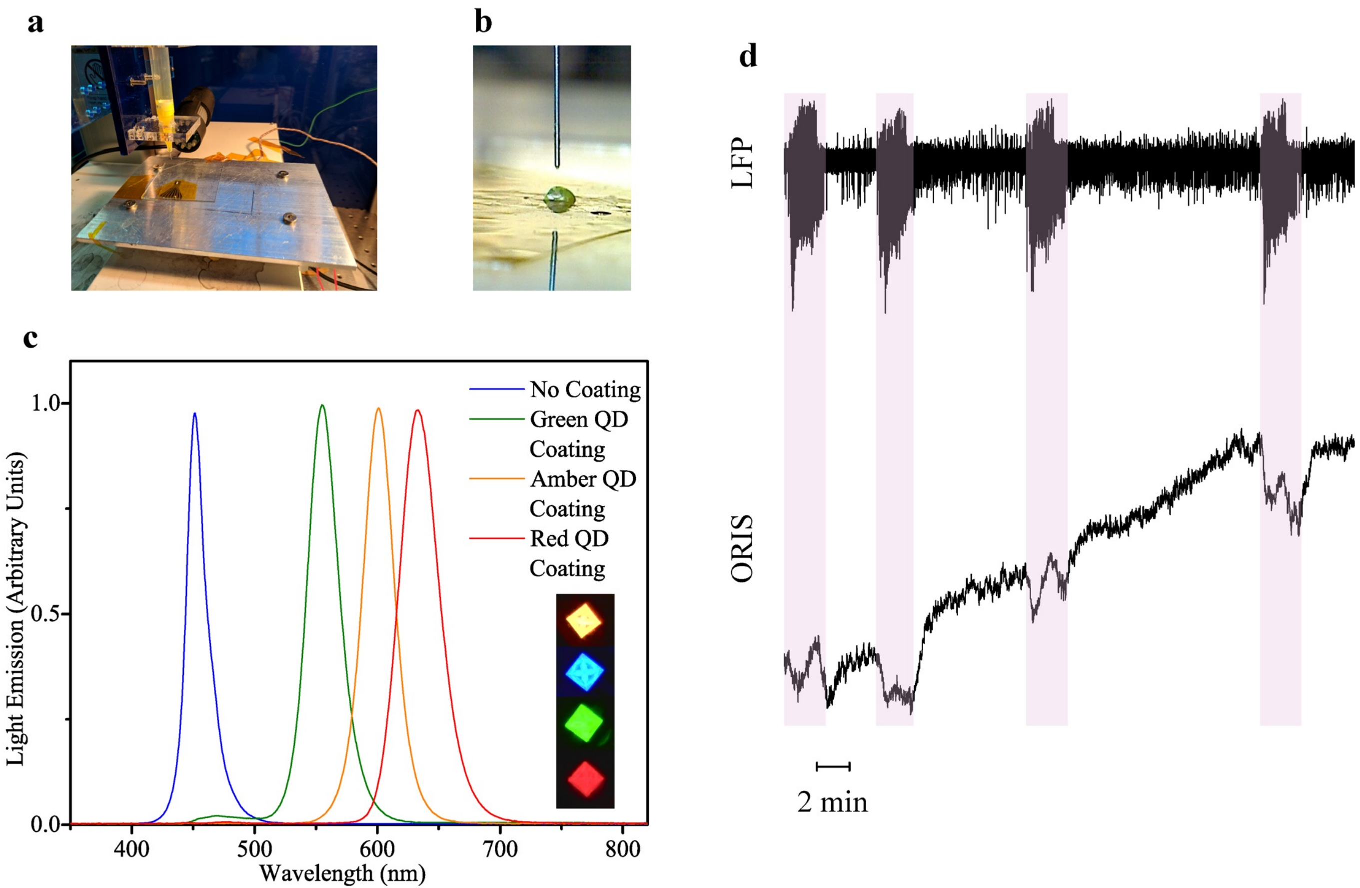
Using uLED as both emitter and detector



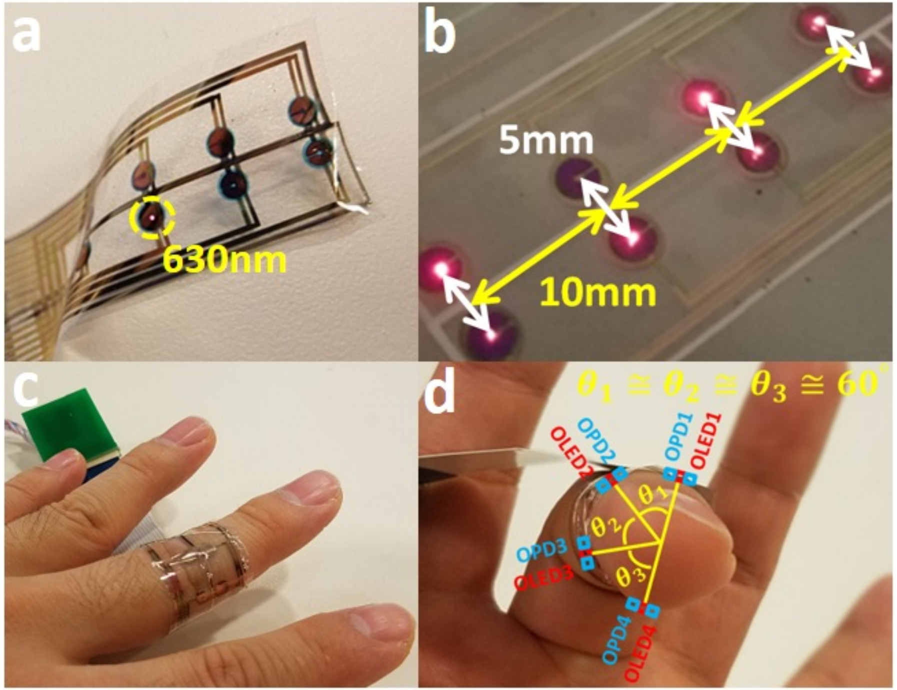
QD raw spectra



Multiple wavelength operation

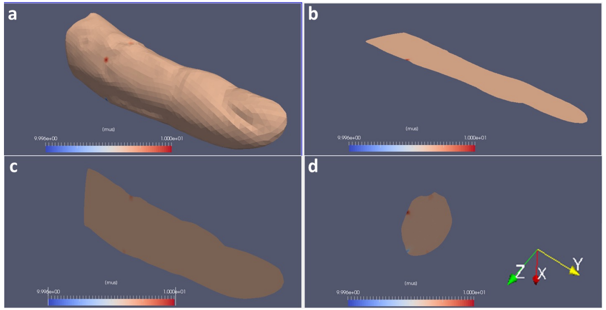


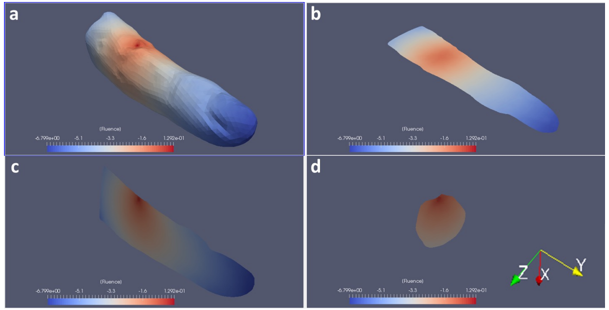
Arthritis mapping using LEDs



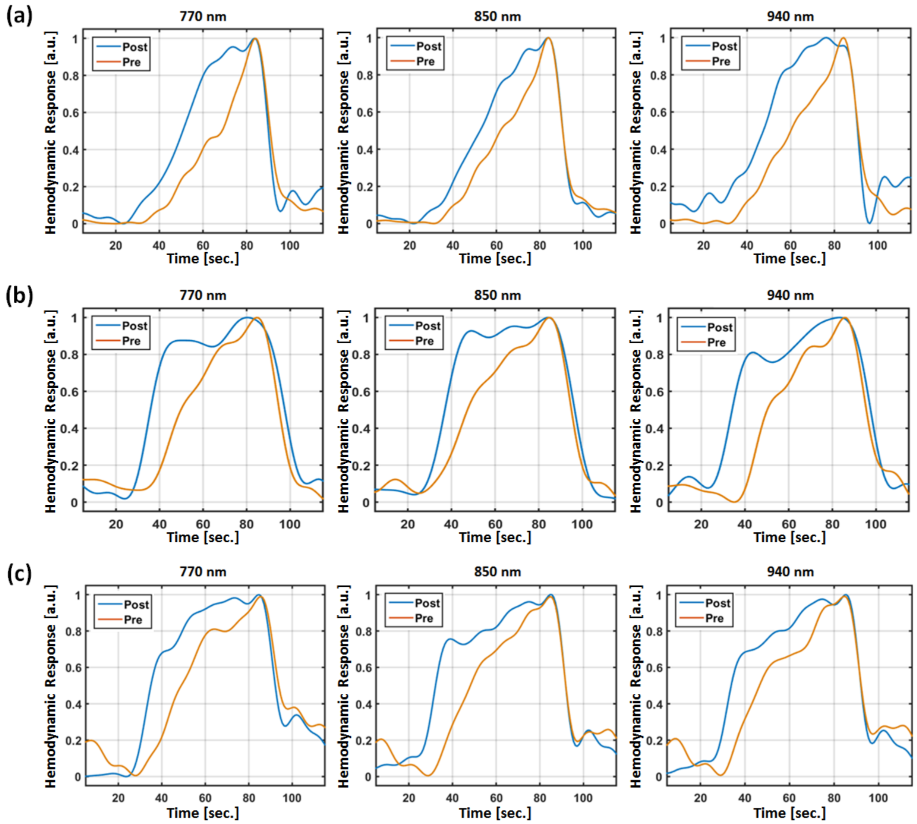
Andreas Heilscher, Theanne Schiros (FIT), Youngwan Kim, Barbara Tripper (UTA), Amy Sperber (FIT), Anastasia Edwards (FIT)

Reconstruction of diffuse data

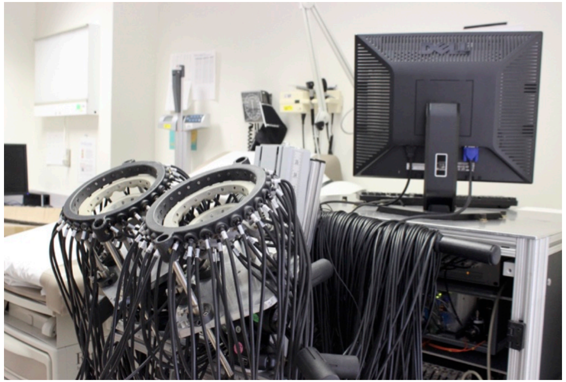




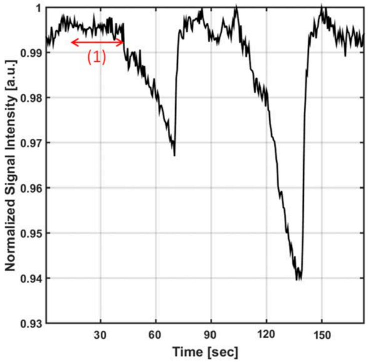
Measurement of diabetic foot

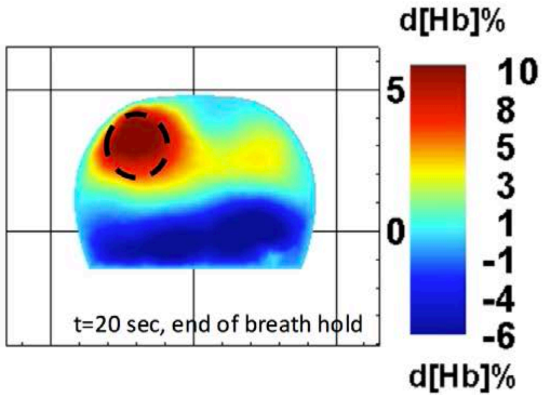


Breast cancer monitoring

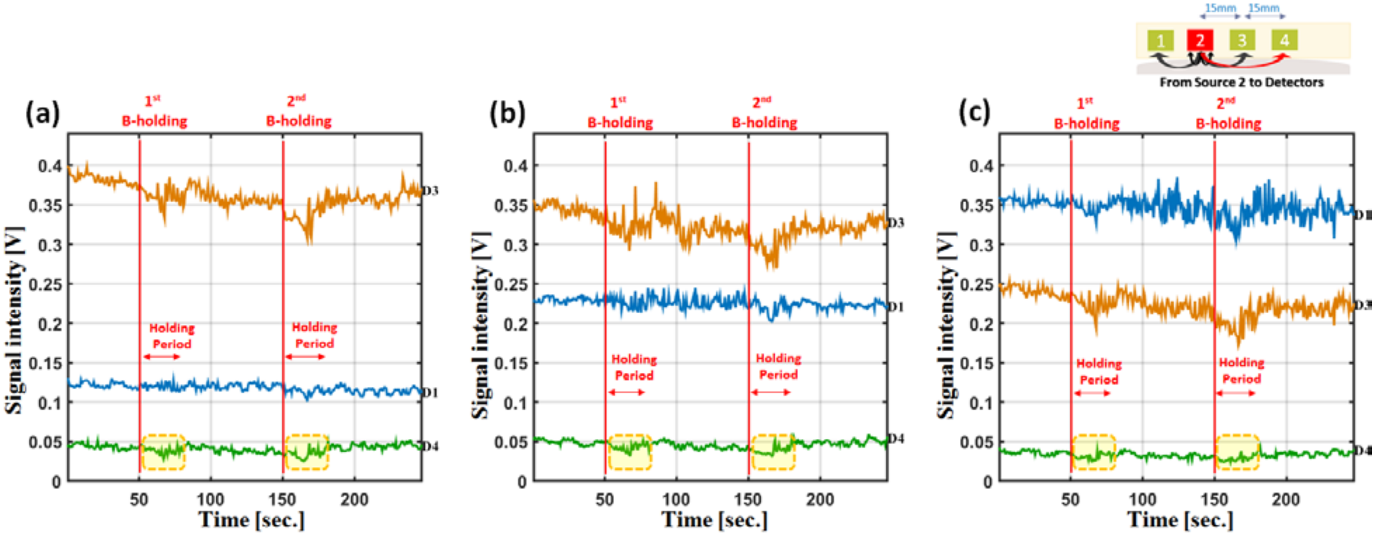


First measurement in breast cancer patient during 20 sec breath hold (@2cm distance)





- Blood vessel regrowth and oxygenation are monitors for the post-surgical healing



Conclusions

- LEDs offer an unmatched performance in generating light
- There are a number of material / device / drive / process issues that could stand additional attention, especially for non-display applications
- There is a co-optimization of size and efficiency at the pixel level for each display type, in addition to significant opportunity for optical emission control
- Both small and large microLED system formats offer opportunities in the non-display space
- Using the LEDs as both emitters and detectors offers some additional opportunities

For more information

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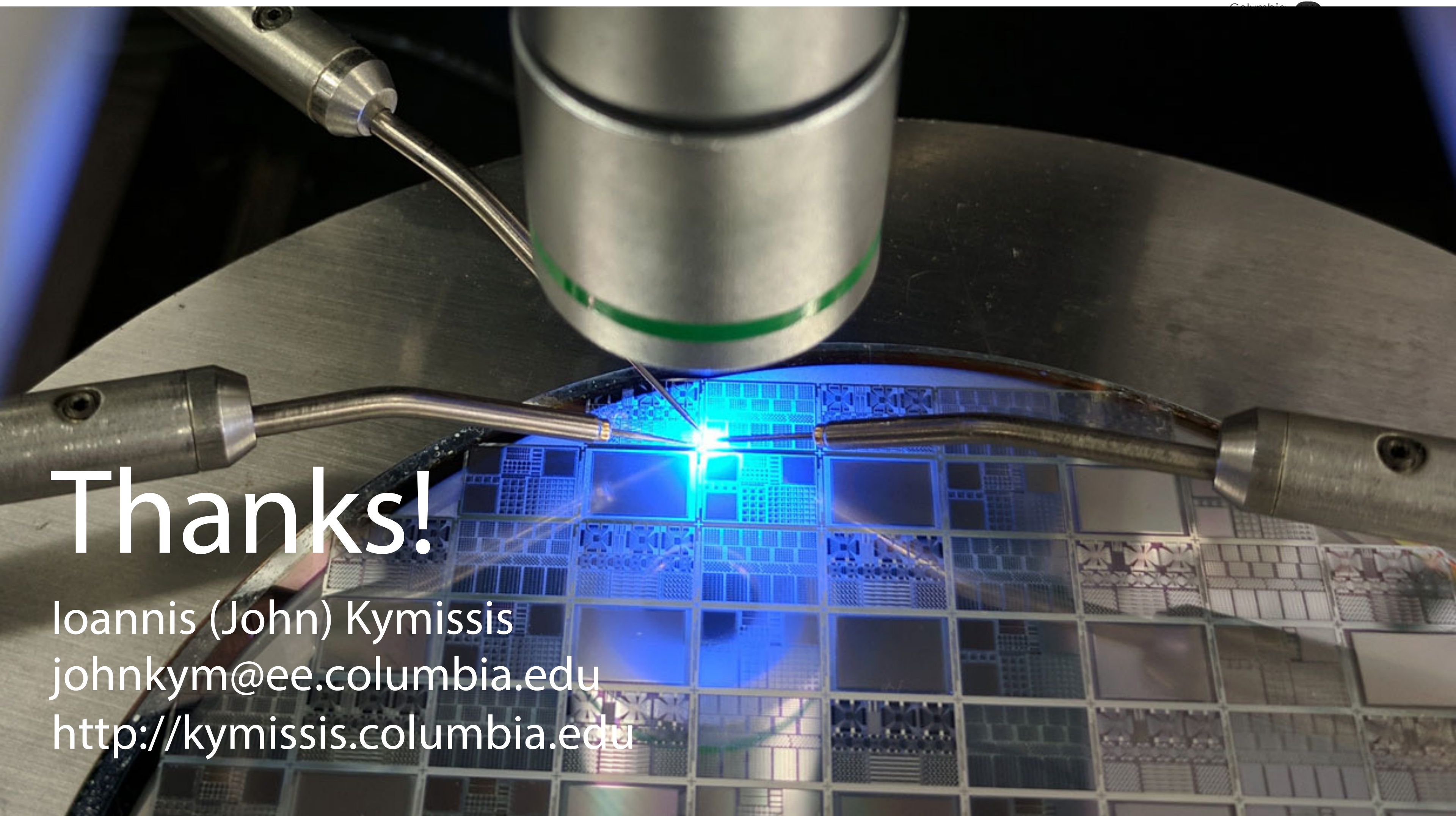

Thanks!

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