Structured Illumination for Communications and Bioscience using GaN Micro-LED Arrays Interfaced to CMOS

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Overview

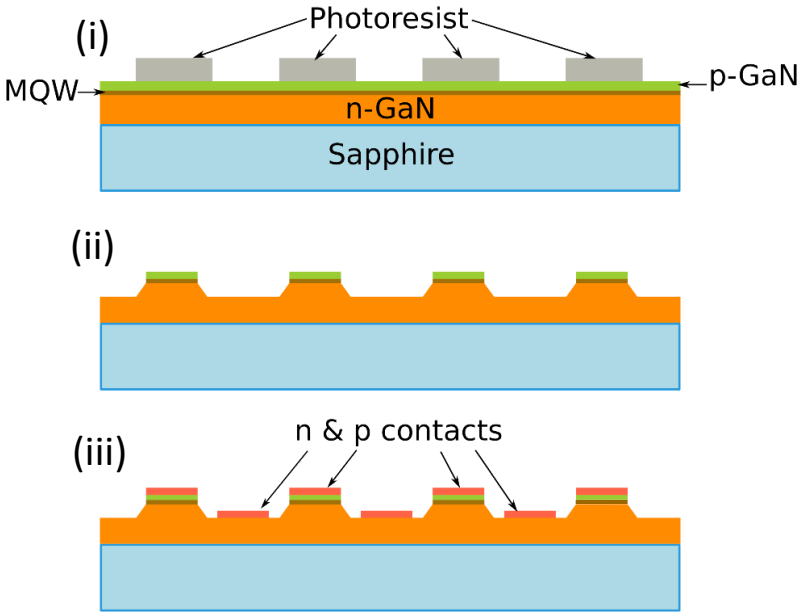
- Institute of Photonics overview
- GaN micro-LEDs
- Integration of micro-LEDs and CMOS drivers
- Application #1: “Smart Lighting” indoor positioning
- Application #2: Visible Light Communication
- Application #3: Bioscience & Optogenetics
- Summary and concluding remarks

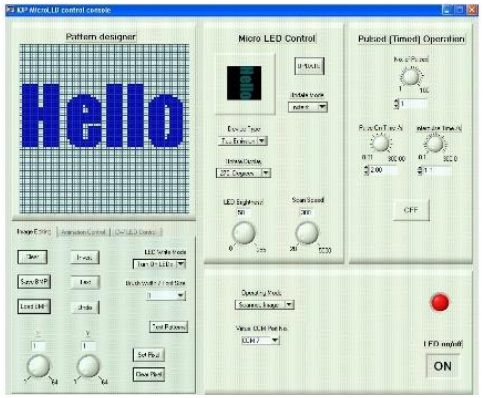
Institute of Photonics – an overview

- Founded in 1995
  - Moved to Technology and Innovation Centre in 2015
  - > 1000 m^2 lab and cleanroom space
  - Approximately 50 staff and PhD students

- Research strengths include:
  - Diamond photonics
  - Semiconductor disc lasers
  - GaN micro-LEDs
  - Neurophotonics
  - Novel photonic materials

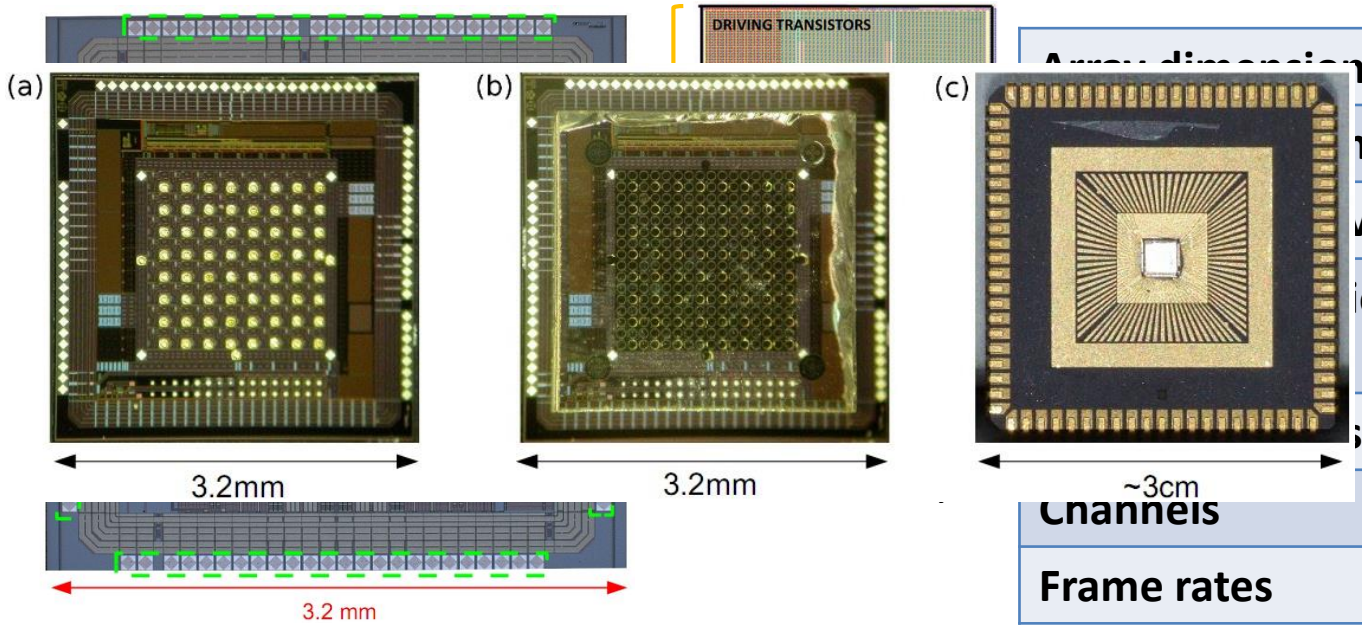
GaN micro-LED arrays





- Typically fabricated on standard MQW GaN LED wafers on *c*-plane sapphire
  - GaN-on-Si substrates have also been used
- Photolithography defines elements. Dimensions typically 1-100 µm per pixel
- Individually-addressable or matrix-addressable, array sizes up to 128×96
- Typical emission ranges from **near-UV** (370 nm) to **green** (520 nm)
- mW-range output power per pixel is typical

CMOS drivers & integration



Array dimensions	8×8, 16×16, 40×10
mA)	≥ 200
V)	3.3 (+ additional 5)
ion	≈ 550 MHz
s)	2 (future Mfps)
Channels	Up to 16
Frame rates	Up to 30 kfps

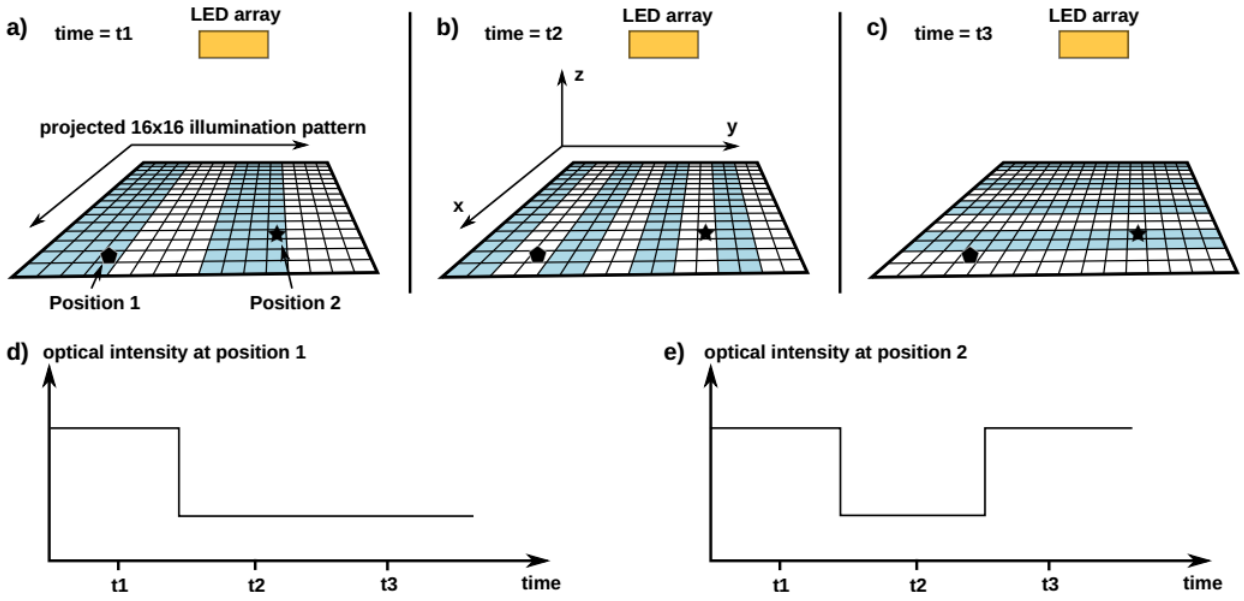
- Designed by Robert Henderson group at University of Edinburgh
- Fabricated using standard low-voltage 0.35 µm CMOS process
- Optimised for generation of intense (high peak current) ns optical pulses
- Individual µLED bump-bonded to individually-controllable CMOS driver

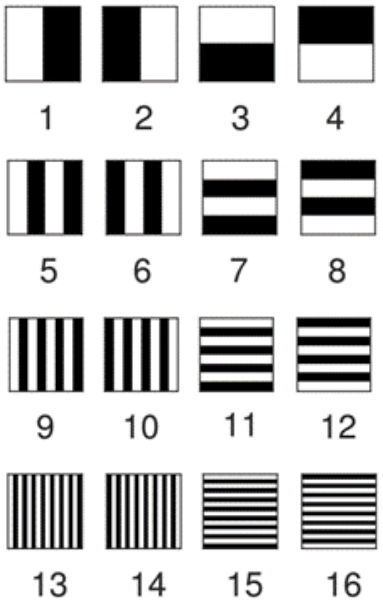
LED-based self-location systems

http://www.lighting.philips.com/main/systems/themes/led-based-indoor-positioning

- Indoor positioning "Smart Lighting" systems beginning to be commercialised
  - Brings GPS-like functionality to indoor environments
- Applications in retail, industry, autonomous control…
- Disadvantage of existing methods:
  - Computational effort at Rx
  - Limitations on modulation techniques that can be used

Positioning using structured illumination

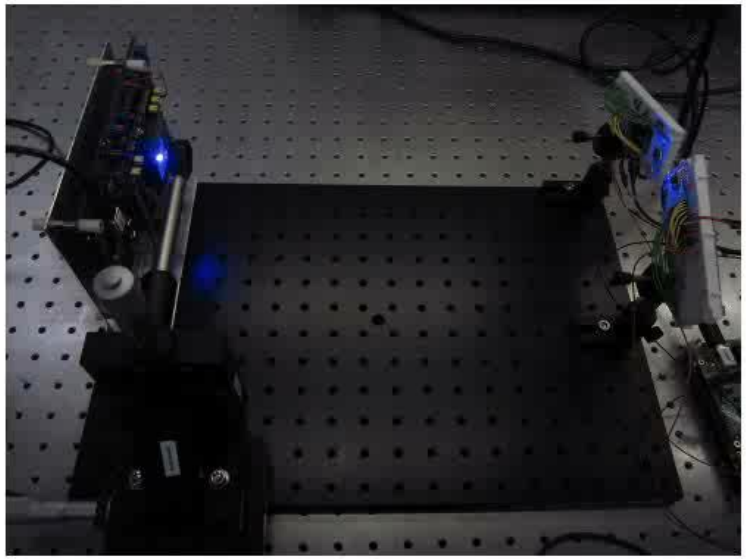




- CMOS/µLED projects pattern sequence in designated area
- Each location receives a unique intensity pattern sequence
- Rx identifies location based on this sequence
- **CMOS driver enables positioning and data multi-access using a single Tx device**
- *Little computation required at Rx, compatible with variety of modulation schemes*

J Herrnsdorf *et al.*, Journal of Lightwave Technology, **35** (12), p2339 (2017)

Smart Lighting: LED-enabled Self-location System



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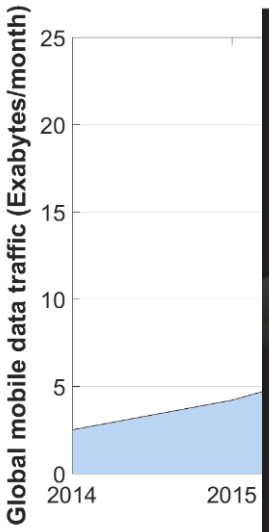
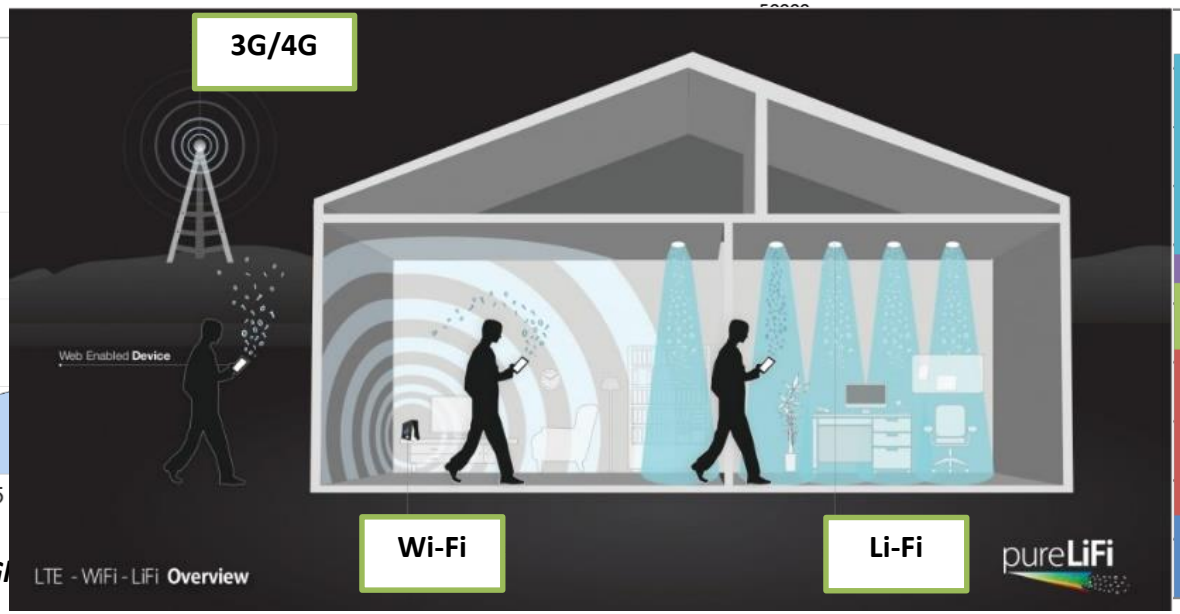
Visible light communications (VLC)



Cisco Systems *Gl*



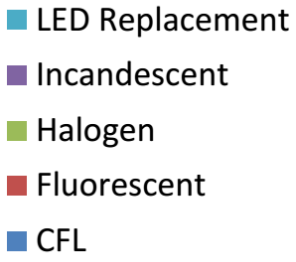
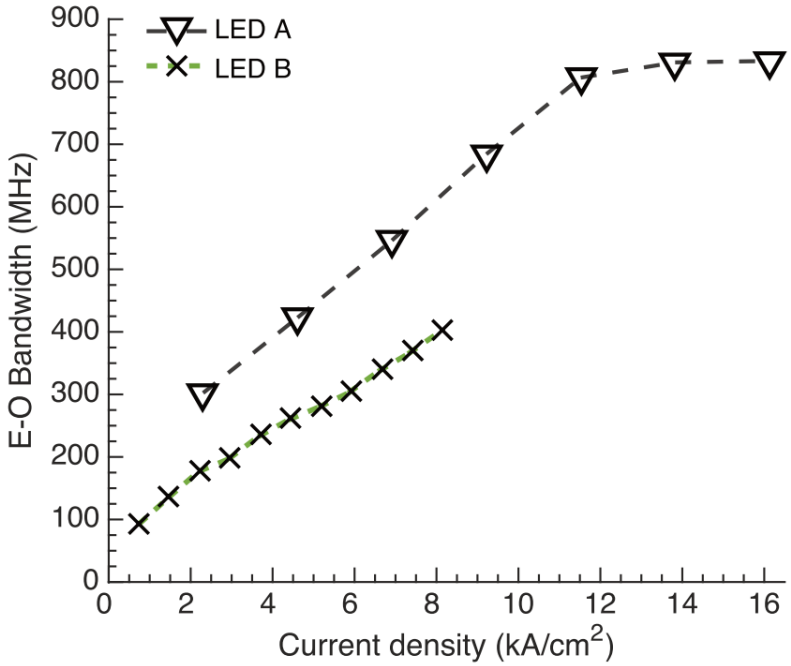


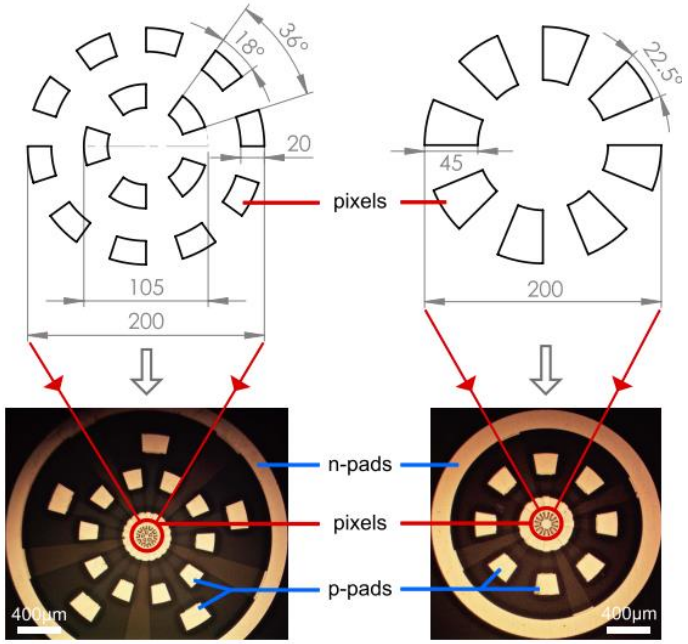
Image from www.purelifi.com

National Research Council
***Assessment of Solid-State Lighting, Phase Two* (2017).**

- Rapid growth in wireless data traffic projected to outstrip improvements in existing RF tech
- Improved efficiency and cost of LED "retrofit" units is driving rapid growth of installed LED fixtures
- Opportunity for GaN LEDs to complement existing technologies:
  - High modulation bandwidth (MHz) compared to incandescent/fluorescent sources
  - Licence-free bandwidth in the visible spectrum

Micro-LEDs for VLC

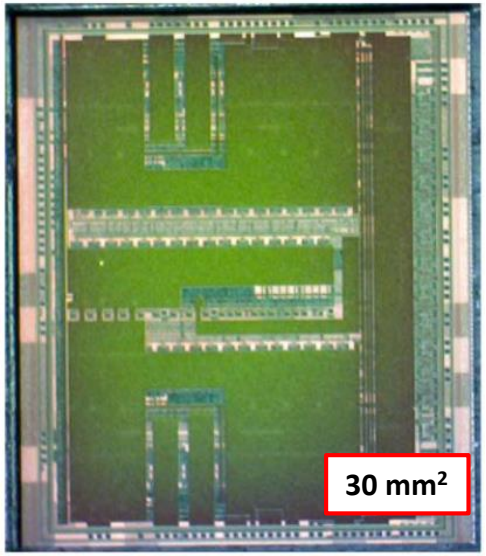




- Bandwidth of micro-LEDs in excess of **800 MHz** – <u>micro-pixellation delivers higher bandwidths</u>.
- Performance limited by carrier lifetime, τ, rather than capacitance.
- Optical data transmission at rates of up to 5 Gb/s **per pixel**

R. Ferreira *et al.*, Photonics Tech. Letters, **28**, 19, 2023-2026 (2016)

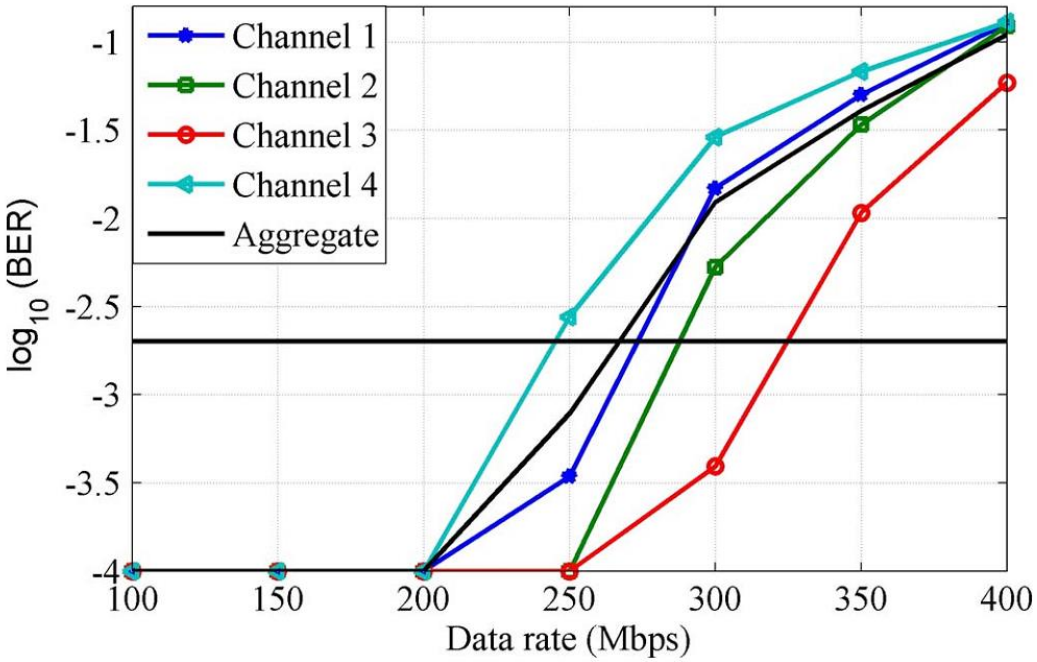
CMOS micro-LED VLC



Max. current per driver (mA)	255
Offset current (mA)	0 to 120 mA
# drivers per chip	4
Driver bandwidth (MHz)	250
DAC resolution	8 bit (ganging), 4 bit (MIMO)
DAC sampling rate (MS/s)	500
Power efficiency	67%
Chip area (mm^2)	30

- Custom-designed for VLC and micro-LEDs
- "Current-steering DAC" – LED current(output power) set by digital word
  - 8 bit resolution
  - 4 drivers – common or independent inputs (SIMO or MIMO)
  - Compatible with variety of modulation schemes (OOK, PAM, OFDM…)

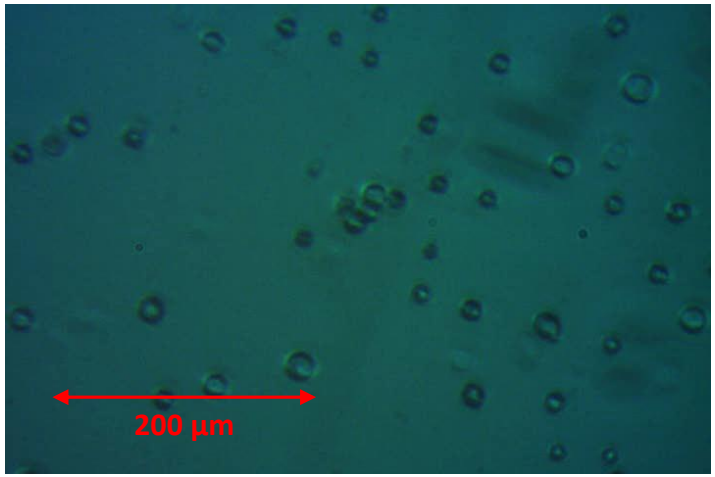
Results



Rajbhandari *et al., IEEE Journal on Sel. Areas in Comms.*, **33**, p1750-1757 (2015).

- On-off-keying (OOK) modulation
- 4 channel MIMO – 4 micro-LEDs imaged to CMOS Avalanche Photodiode array
- Total aggregate data rate **1 Gb/s over 1 m** of free space
- More recent results demonstrate **7.48** Gb/s using 9 channel MIMO (*Journal of Lightwave Technology, in press)*

CMOS micro-LEDs for bioscience



Opto-electronic trapping

- Micro-LED array replaces bulky DMD or LCD display
- Applications in cell-sorting & monitoring cell interactions

A. Zarowna-Dabrowska *et al., Optics Express,* **19**, 1714-1720 (2011)

Time-resolved fluorescence lifetime measurements

for e.g. explosives sensing and biomedical applications

B. Rae *et al.*, J Phys. D, **41**, 094011 (2008)
Y. Wang *et al*., *AIP Advances,* **1**, 032115 (2011)

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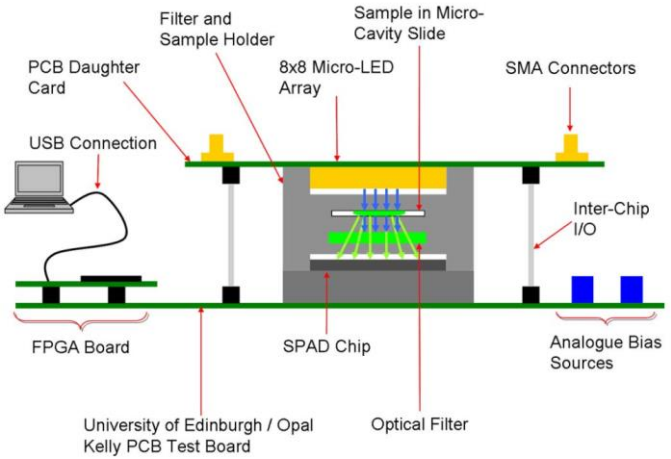

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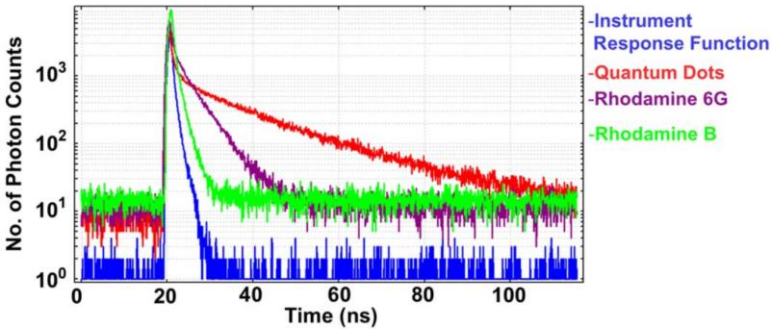

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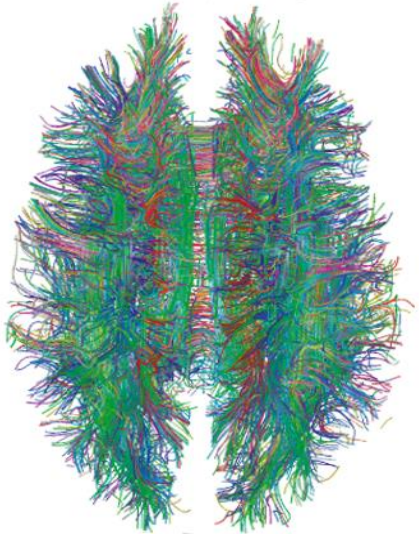
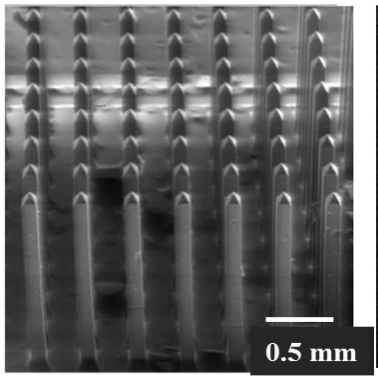
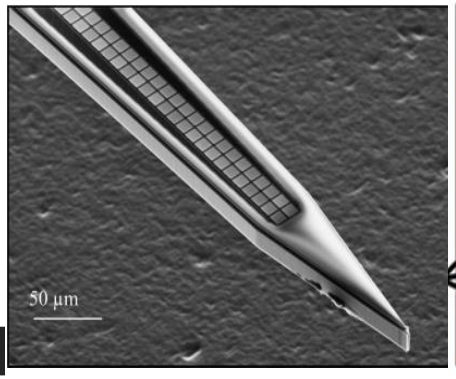
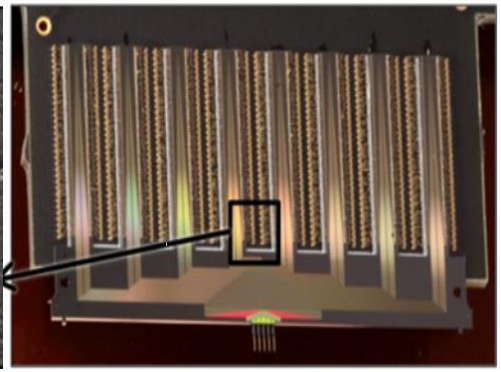
Neurophotonics

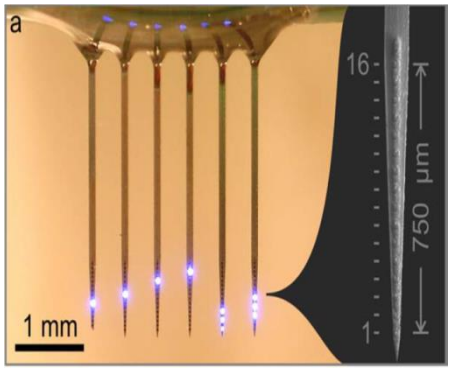
- The inherent complexity of the brain presents many challenges
- To gain a better understanding:
  - Requirement to record vast amounts of data from many channels
  - Accurately stimulate nerve populations and correlate behaviour (eg. Optogenetics)







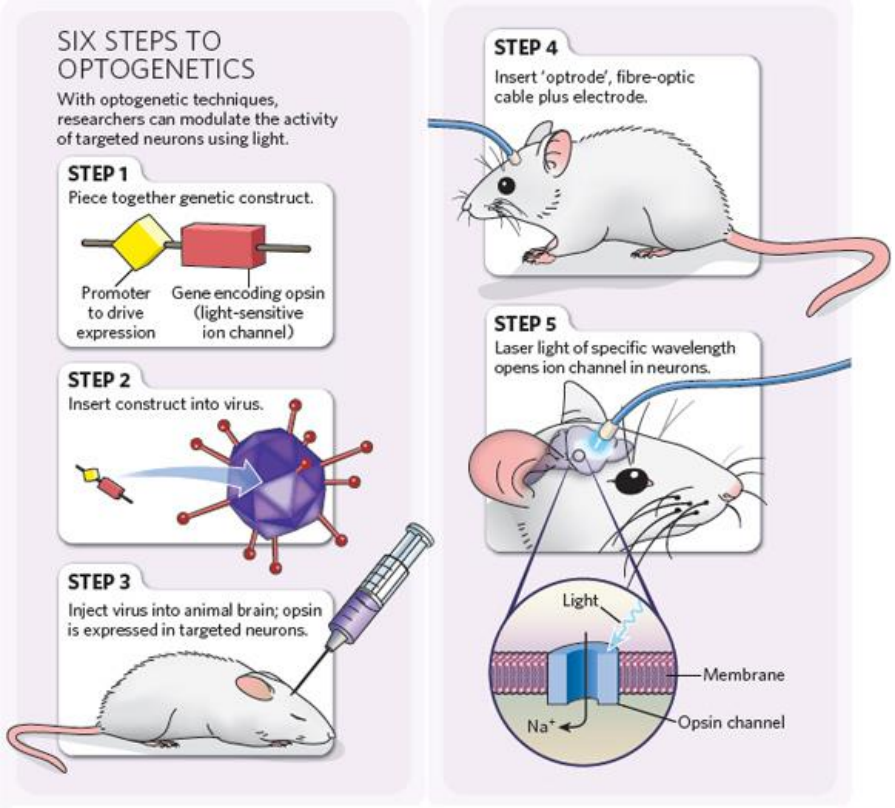




Abaya, Tanya VF et al., 2014

Scholvin et al. IEEE Trans. Biomed. Eng., 63 (1) 2016

How does optogenetics work?



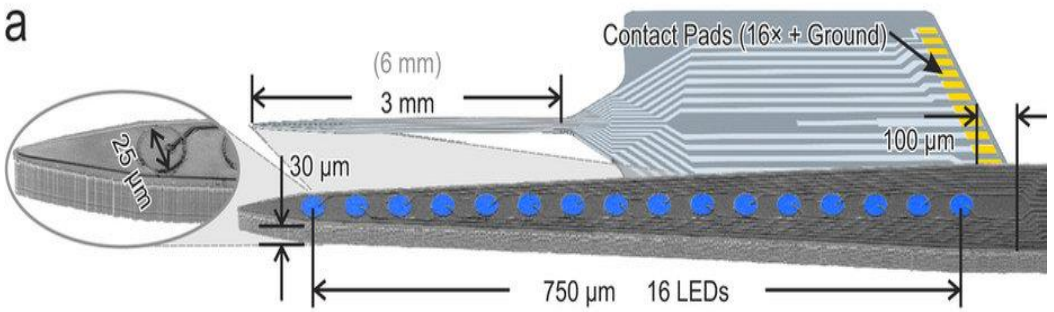
- Naturally available light sensitive genes present in certain organisms such as algae can be incorporated into other types of cells e.g. mammalian nerve cells
- Cells that express light sensitive channels can be controlled by the type of promoter introduced with the gene encoding opsin.
- Light sources such as fibers or probes can then be used to activate/deactivate transfected cells

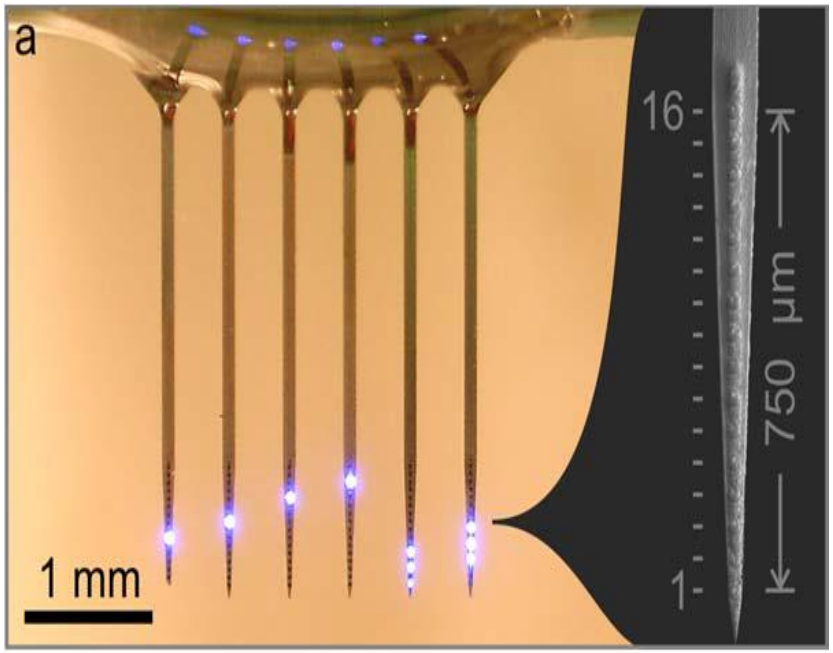
Published online 5 May 2010 | *Nature* **465**, 26-28 (2010) | doi:10.1038/465026a

Silicon based µLED array needle probes

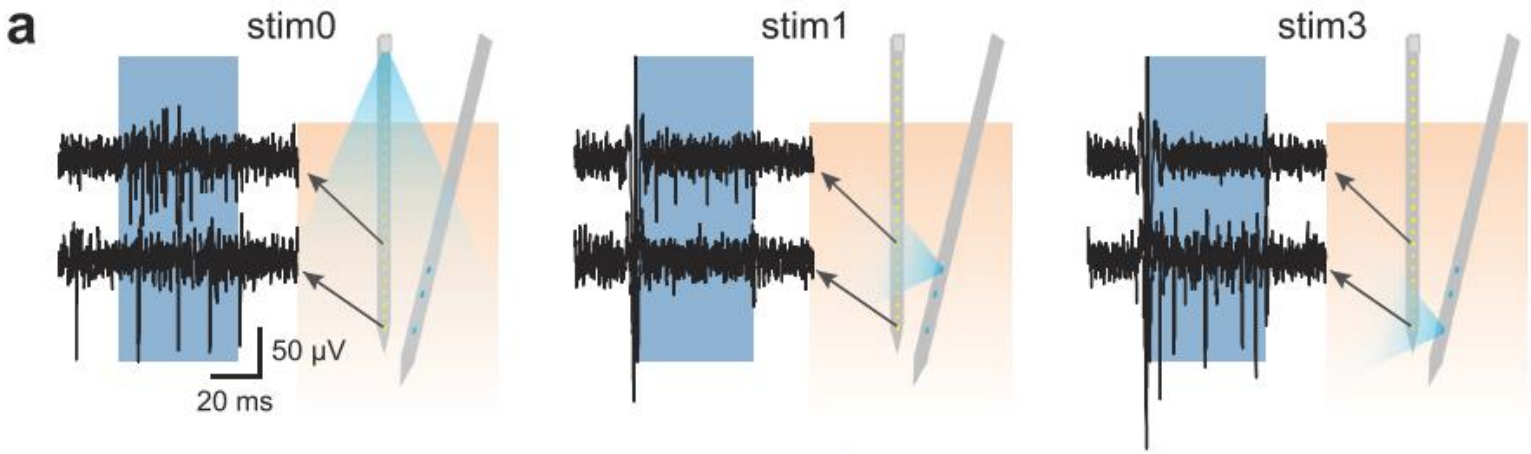
- High-density µLED needle probes created on GaN-on-Si substrate.
- Shank design consists of:
  - 16 µLEDs (25um diameter, 50um pitch).
  - Width - 100 µm, tapering to 1µm
  - Thickness- ~~40 µm.
  - Length - 3mm.

- This design has been scaled up to multi-shank probes with 6 shanks containing 96 individually addressable LEDs





Depth-specific optogenetic control



R. Scharf *et al., Scientific Reports*, **6**, 28381 (2016).

- Control of micro-LEDs along shank allows depth-specific excitation of cells
- Different cell populations activated *in vivo*
- Future work to include electrodes and LEDs on single shank
- Opportunities to use CMOS for:
  - Control of micro-LEDs
  - Amplification and digitisation of electrical signals

Summary

- GaN micro-LEDs:
  - High brightness micro-scale displays
  - Fast (Hundreds of MHz) modulation
  - (Sub)-nanosecond optical pulses
  - Can be integrated with CMOS electronics
- Demonstrated applications include:
  - “Smart lighting”
  - Visible light communications
  - Bioscience, neurophotonics
  - High-brightness micro-displays

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