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

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Overview

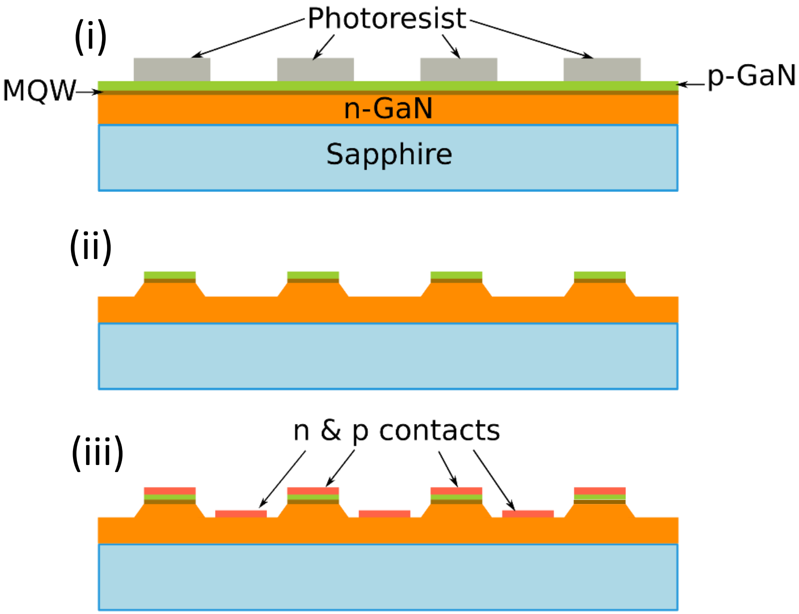
University of Strathclyde Science

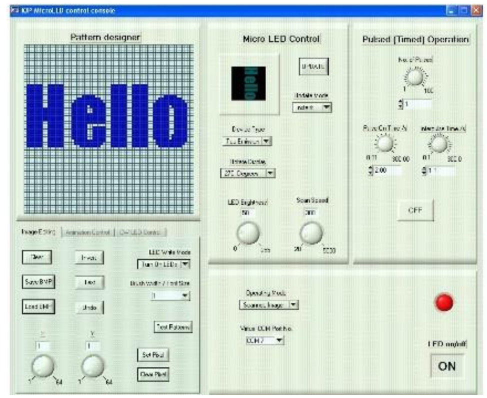
- Institute of Photonics overview
- GaN micro-LEDs
- Integration of micro-LEDs and CMOS drivers
- Application #1: “Smart Lighting” indoor positioning
- Application #2: Visible Light Communication
- Application #3: Bioscience & Optogenetics
- Summary and concluding remarks

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

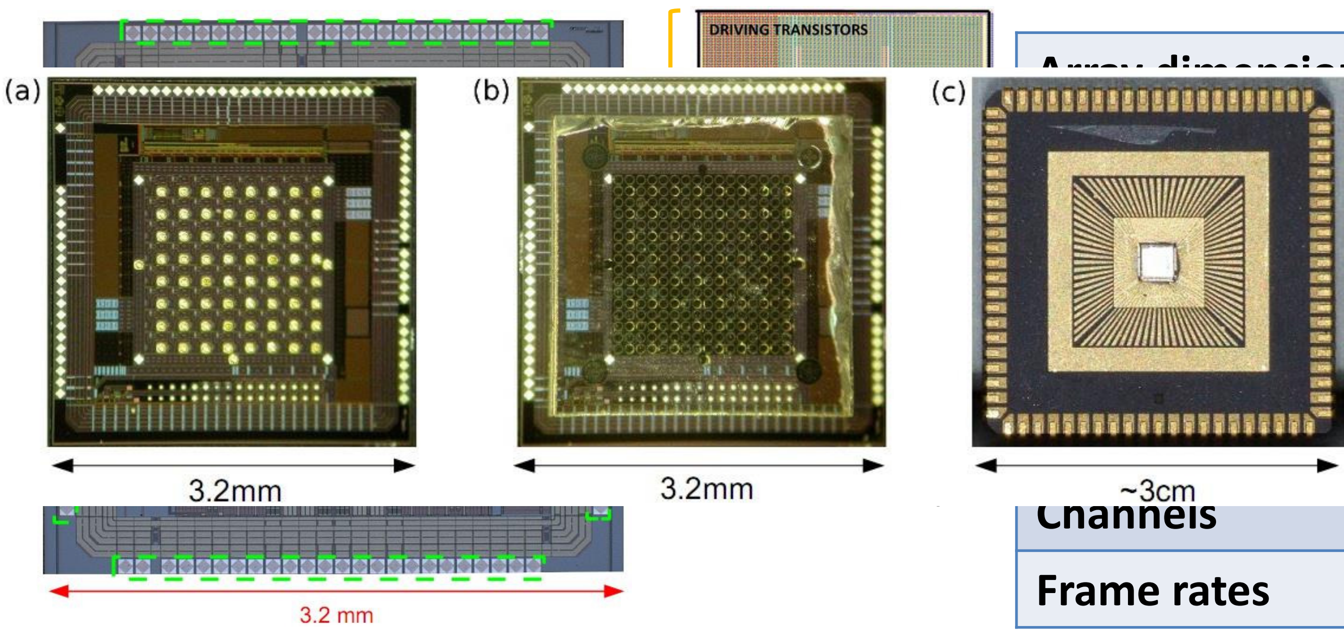
GaN micro-LED arrays





- 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

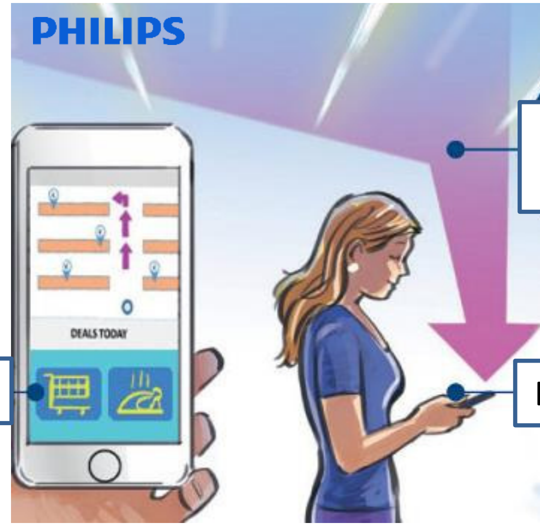
CMOS drivers & integration



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

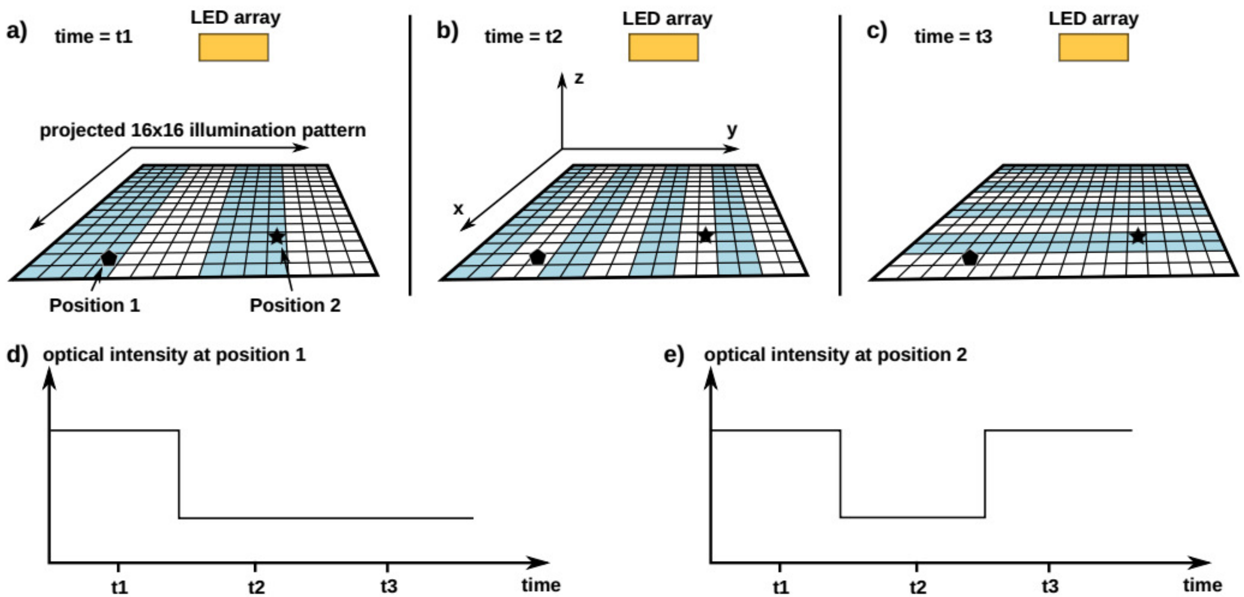
LED-based self-location systems

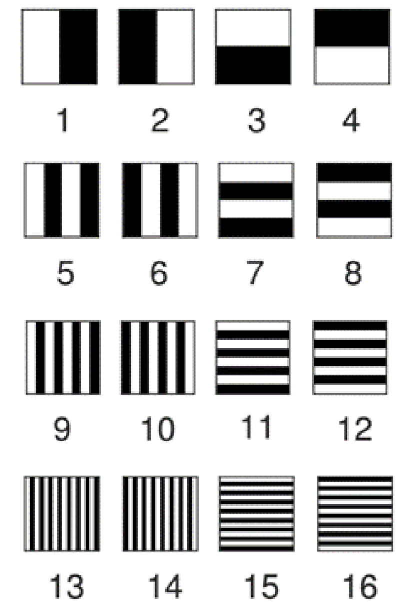


http://www.lighting.philips.com/main/systems/themes/led-based-indoor-positioning

- 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

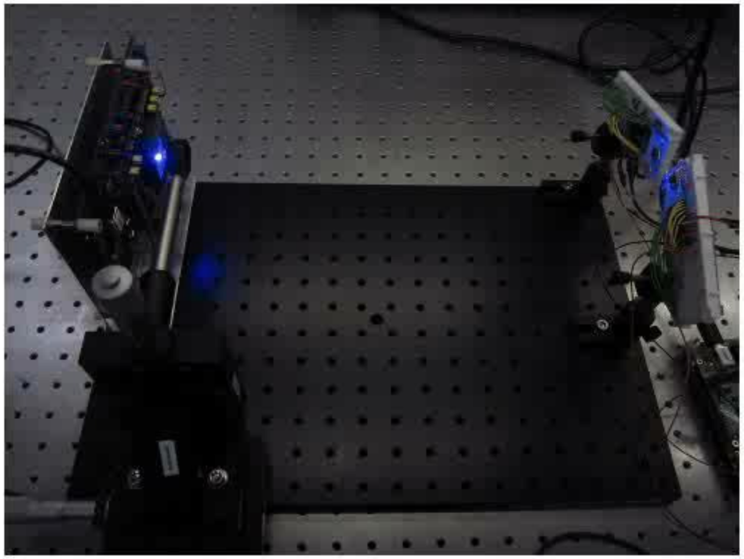




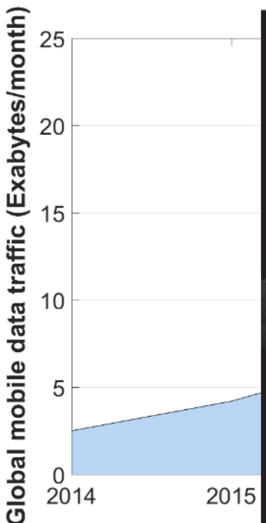
- CMOS/µLED projects pattern sequence in designated area
- Each location receives a unique intensity pattern sequence
- Rx identifies location based on this sequence
- **CMOS driver enables positioning and data multi-access using a single Tx device**
- *Little computation required at Rx, compatible with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

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

Smart Lighting: LED-enabled Self-location System



Visible light communications (VLC)



Cisco Systems Gl

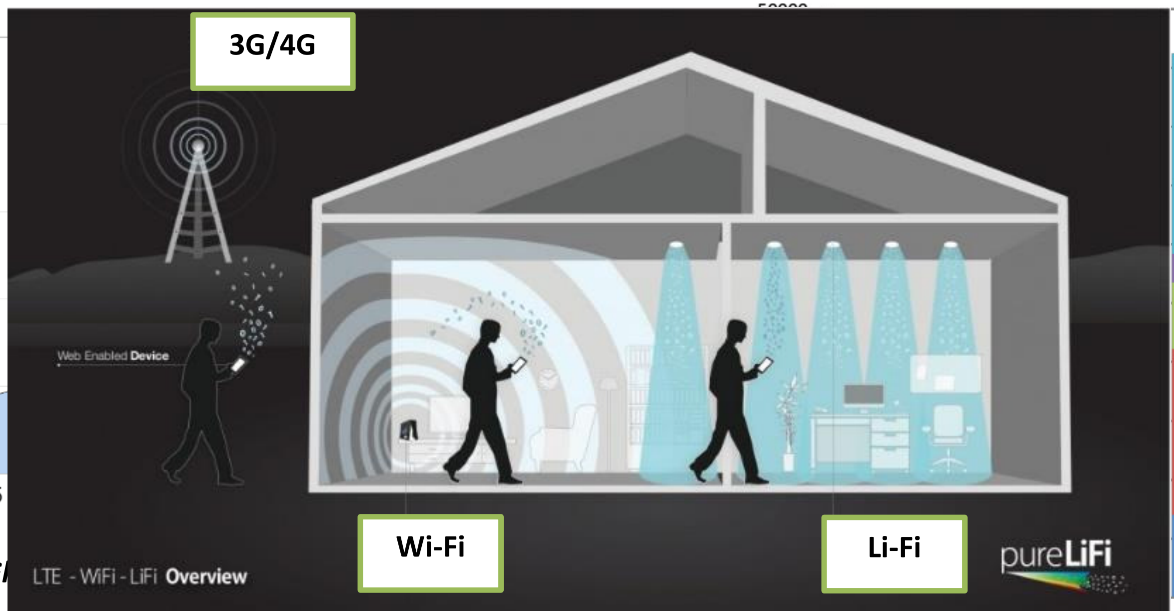
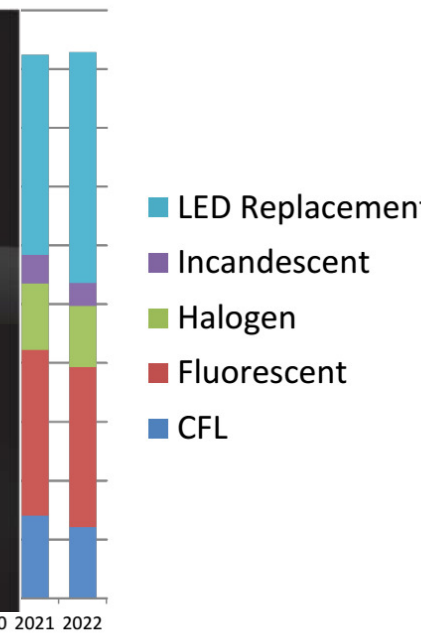


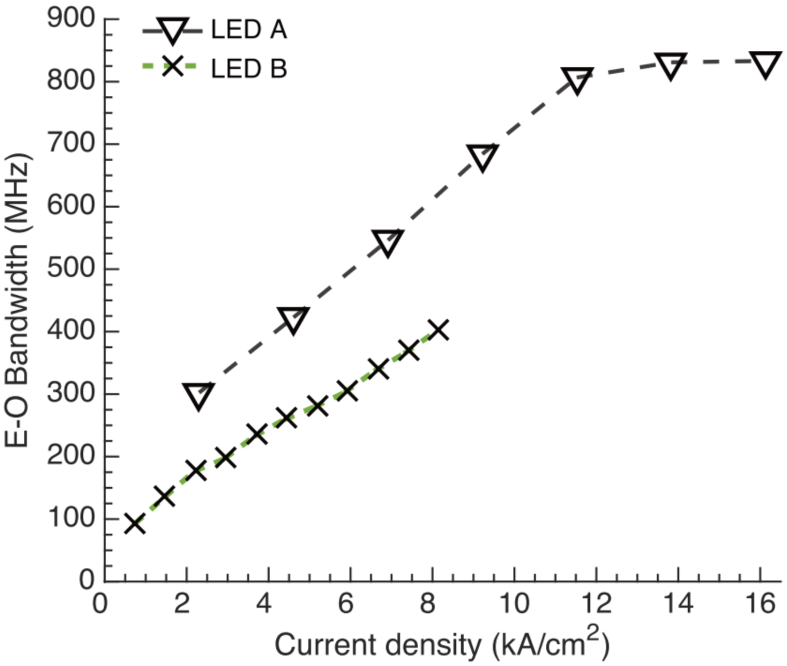
Image from www.purelifi.com

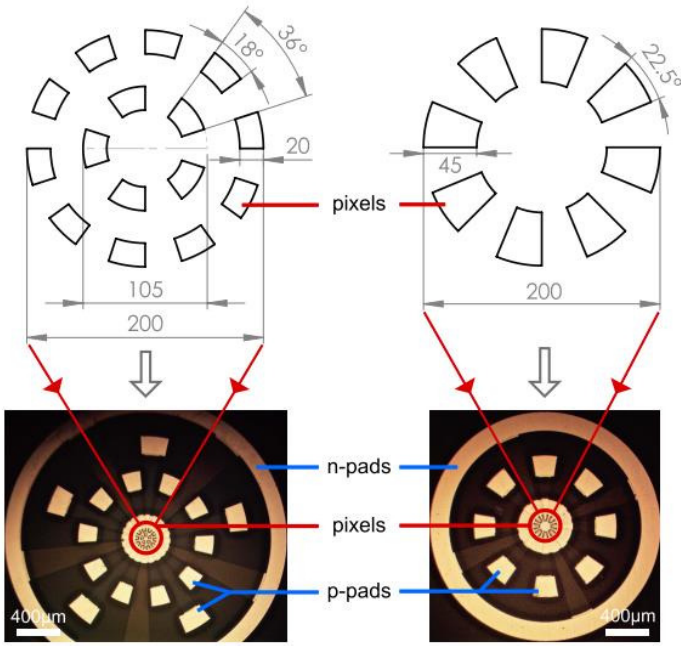


National Research Council
***Assessment of Solid-State Lighting, Phase Two* (2017).**

- 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

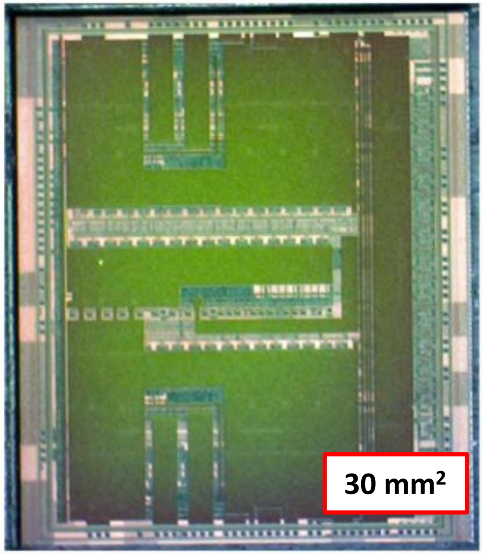




- Bandwidth of micro-LEDs in excess of **800 MHz** – <u>micro-pixellation delivers higher bandwidths</u>.
- Performance limited by carrier lifetime, τ, rather than capacitance.
- Optical data transmission at rates of up to 5 Gb/s **per pixel**

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

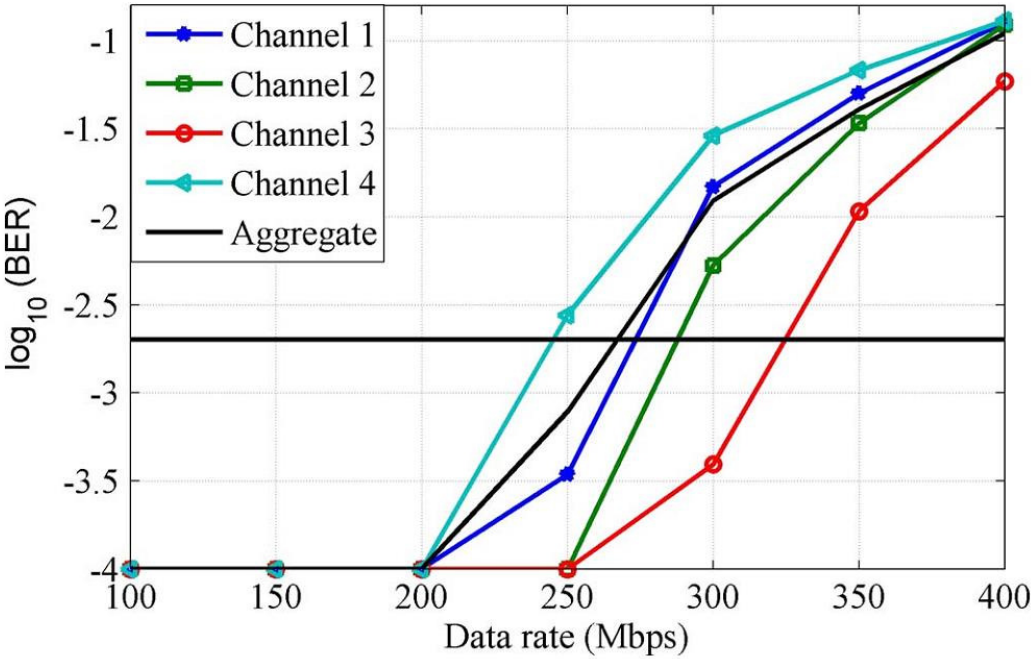
CMOS micro-LED VLC



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…)

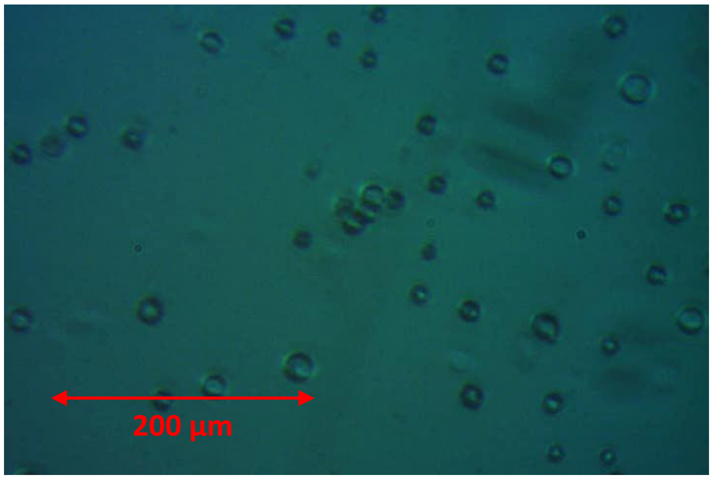
Results



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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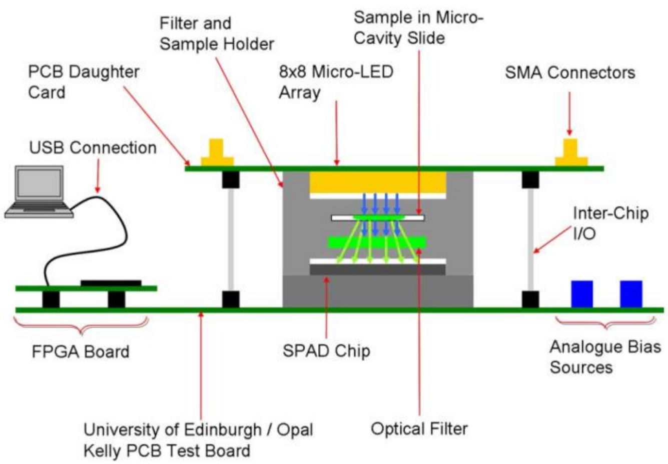

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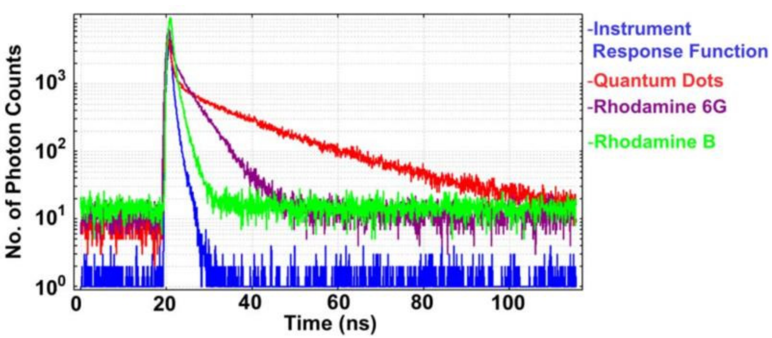

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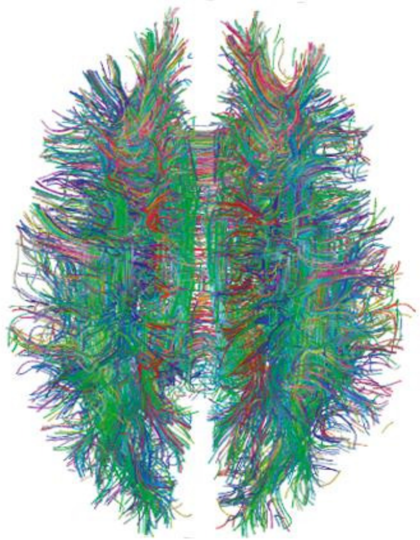
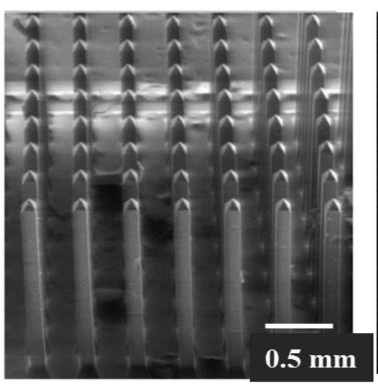
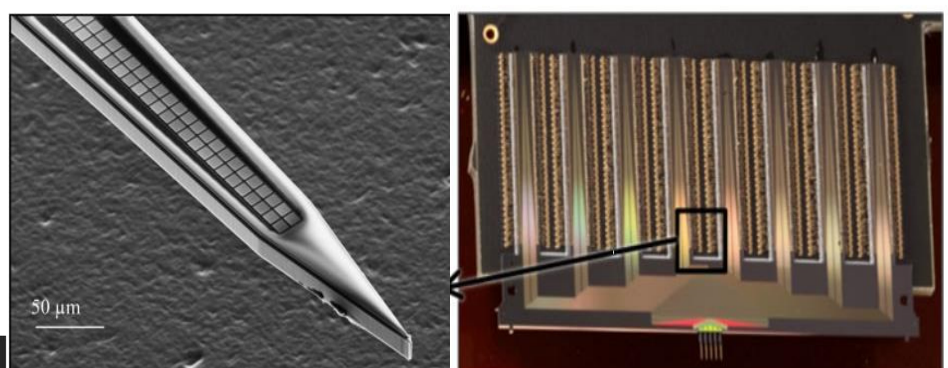
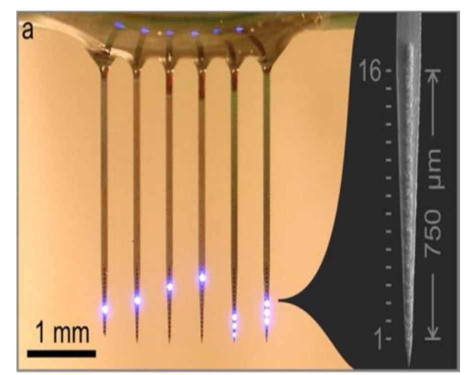
Neurophotonics

- 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)





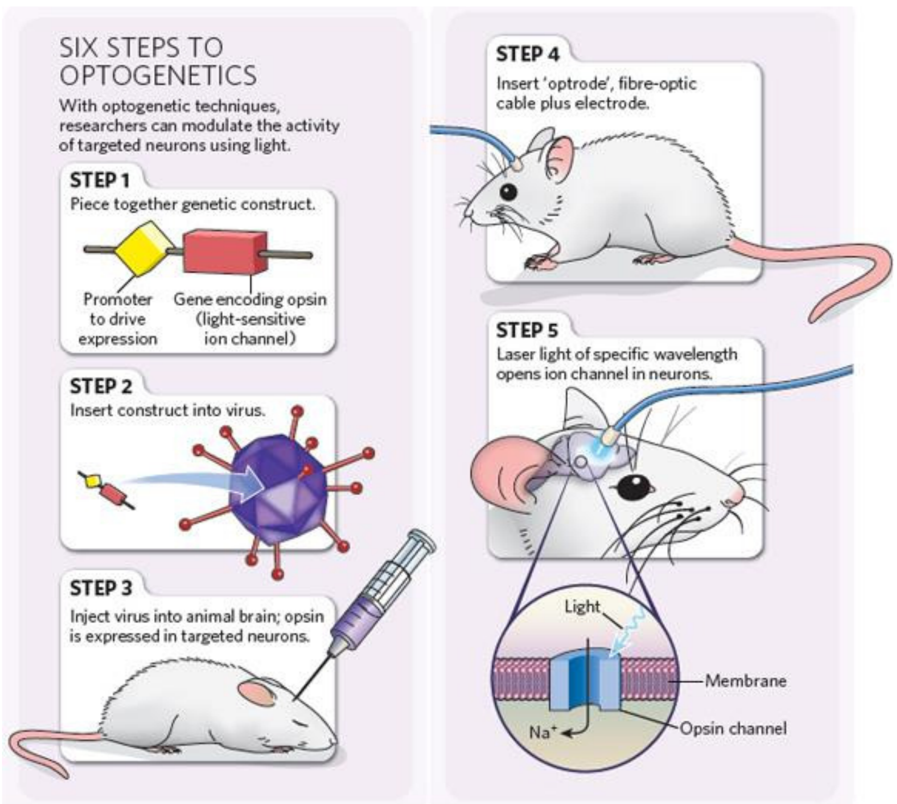




Abaya, Tanya VF et al., 2014

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

How does optogenetics work?



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

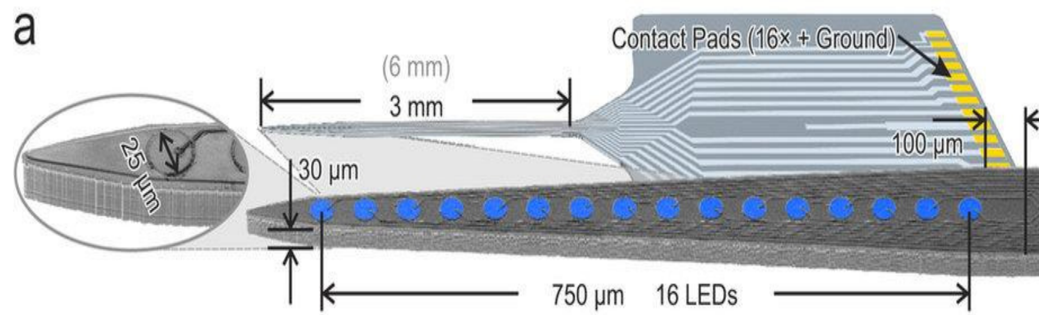
- Naturally available light sensitive genes present in certain organisms such as algae can be incorporated into other types of cells e.g. mammalian nerve cells
- Cells that express light sensitive channels can be controlled by the type of promoter introduced with the gene encoding opsin.
- Light sources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

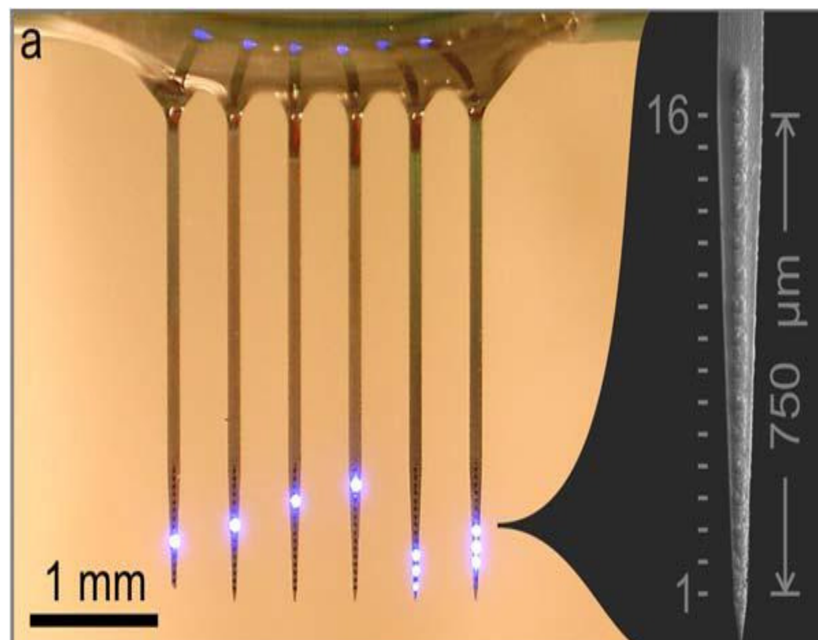
Silicon based µLED array needle probes

University of Strathclyde Science

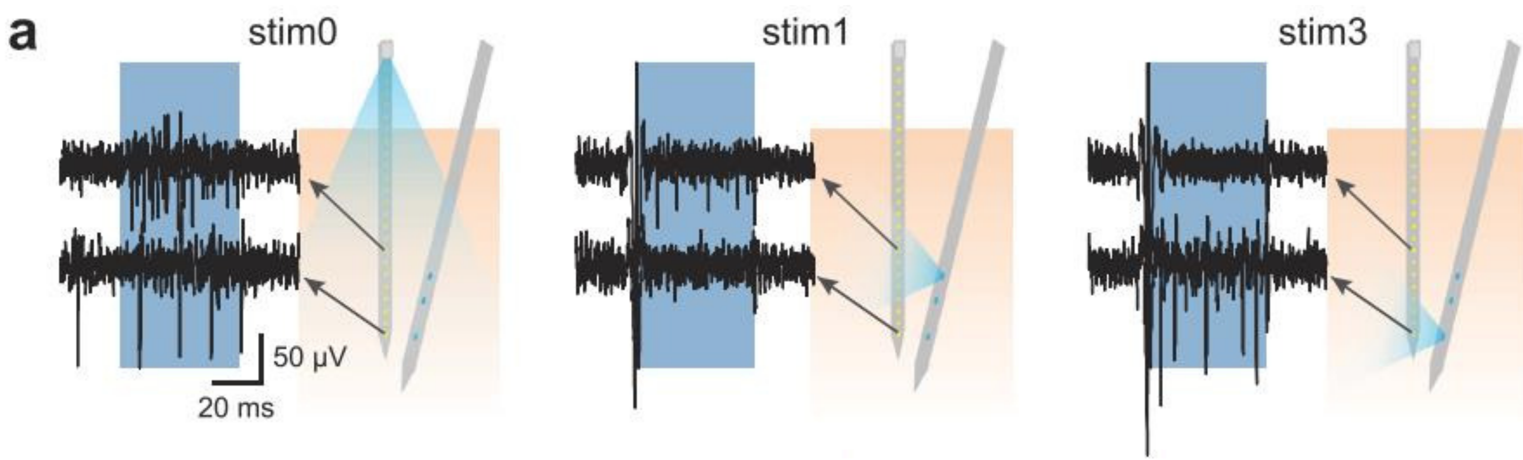
- High-density µLED needle probes created on GaN-on-Si substrate.
- Shank design consists of:
  - 16 µLEDs (25um diameter, 50um pitch).
  - Width - 100 µm, tapering to 1µm
  - Thickness- ~~40 µm.
  - Length - 3mm.

- 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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Thank you for your attention

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