Scalable optical excitation and modulation of semiconductor nanowire emitters

Zhongyi Xia[1,*], Dimitars Jevtics[1], Benoit Guilhabert[1], Jonathan J.D. McKendry[1], Hark Hoe Tan[2], Chennupati Jagadish[2], Martin D. Dawson[1], and Michael J. Strain[1]

[1]Institute of Photonics, Department of Physics, University of Strathclyde, Glasgow, United Kingdom
[2]Department of Electronic Materials Engineering, Research School of Physics, The Australian National University, Australian Capital Territory, Australia
**Corresponding author. Author e-mail address: zhongyi.xia@strath.ac.uk*

Abstract: We show that individually addressable micro-LED-on-CMOS arrays can be used as scalable optical excitation sources for arrayed semiconductor nanowire devices. This approach is used to demonstrate optical modulation at MHz rates of heterogeneously integrated nanowire-emitters. © 2023 The Author(s)

1. Introduction

Semiconductor nanowires are quasi-one-dimensional devices, which are attracting a great deal of attention in the nano-photonics community due to their unique optical and electrical properties [1]. To date, nanowire-based coherent light sources from a variety of material platforms, such as II-VI's, III-V's, III-nitrides, and perovskites, have been reported, covering emission wavelengths from UV to NIR [2]. Due to their low threshold, low energy consumption and high refractive index, they have become promising candidates for on-chip lasers in next-generation photonic integrated circuits. However, the inter-device inhomogeneity in populations of nanowire devices is a significant issue for their further use in photonic systems on a chip.

To overcome this challenge, the combination of both heterogeneous integration and large-scale optical characterization/binning techniques enables not only the selection of devices with desirable emission parameters, but also their further integration into spatial arrays on-chip [3]. However, the conventional method of optical excitation, using a laser source, only permits pumping of a single nanowire or bundle of nanowire devices at a time, prohibiting any large-scale and individually addressable nanowire device architectures. Here, by contrast, a micro-LED-on-CMOS array is shown to controllably optically excite pre-assembled arrays of pitch-matched target nanowires and is used to demonstrate optical modulation (on-off keying) in the range of 10's of MHz using an array of InP nanowires.

2. Optical excitation using Micro-LED-on-CMOS system

A CMOS-controlled (bump-bond-integrated) InGaN micro-LED array with measured central peak wavelength of 405 nm was used as an optical pump source to achieve optical emission in the nanowires [4]. As depicted in Fig. 1, the FPGA-based CMOS board allows the control of micro-LED pixels both individually and in parallel [5] as each pixel in the 16 x 16 array has its own separate CMOS driver. These can then directly, or through free-space optics, be projected onto nanowire samples and used to excite multiple spatially isolated devices in parallel, where the maximum number of parallel devices equals the number of pixels (256 pixels for the micro-LED array used here). The 72 µm diameter micro-LED pixels used in this work had a modulation bandwidth of ~ 36 MHz, with a single pixel emitting an average optical power of 1 mW.

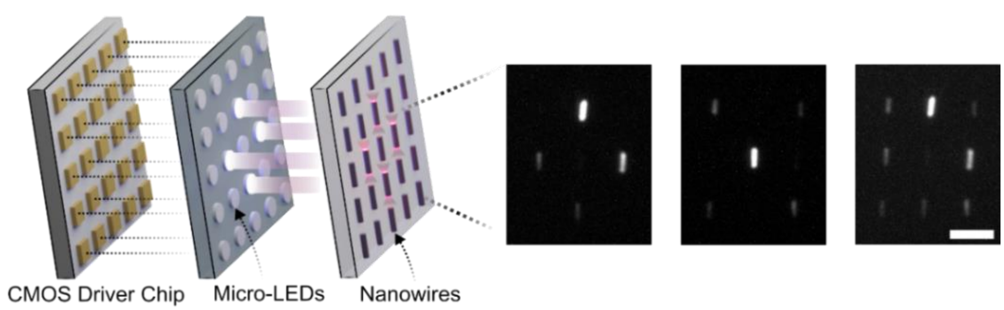

Figure 1: *An exploded-view schematic diagram showing the three-layer system: CMOS driver chip, micro-LEDs and nanowire array. By generating different optical patterns from the micro-LED array, it becomes possible to activate target nanowire devices. Projected pattern examples of excited nanowire arrays are shown in images on the right, forming 'diamond', 'X', and 'square' patterns - scale bar 20 µm*

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3. Optical modulation of semiconductor nanowire emitters

Target InP nanowire devices were transferred from their growth substrate and assembled onto a z-cut quartz substrate using a micro-transfer-printing technique (see ref. [1] for information). Selected micro-LED pixel emission was then projected onto individual nanowires and groups of nanowire emitters using free-space optics (see ref. [4] for the micro-PL system description). This allows us to collect the light directly from the nanowire facets, i.e., in-plane to their emission. To record their emission spectrum, a fiber-based spectrometer was used to capture the light emitted from the nanowire facets. Fig. 2(a) shows a measured spectrum from a group of nanowire devices. Inset shows the excitation spot projected from a single micro-LED pixel onto a group of two ~ 12 µm-long nanowire devices.

An external frequency generator was then connected to the CMOS board, allowing control of the modulation frequency of the micro-LEDs. A synchronized output from the same frequency generator was connected to trigger a single photon avalanche diode camera which ran in time-correlated single-photon counting mode, thus enabling us to take time-domain modulation measurements from both micro-LEDs and nanowire devices.

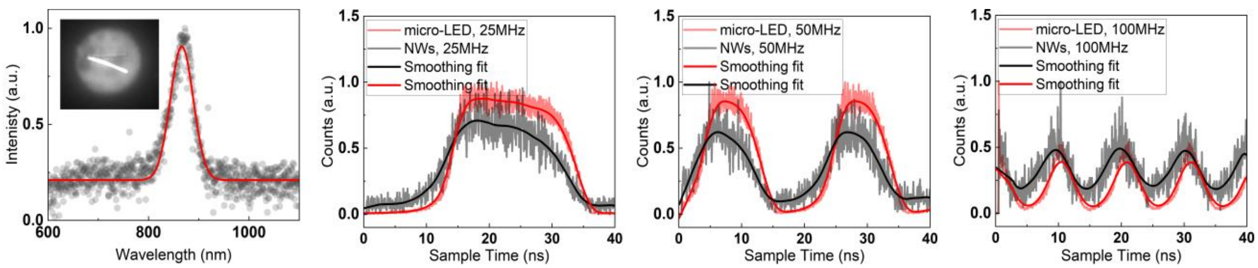

Figure 2: *(a) Spectrum from a bundle of InP nanowire devices optically excited using a single micro-LED pixel. Inset shows brightfield image of single micro-LED output projected onto a group of nanowires. (b-d) Time-domain modulation measurements (on-off keying) collected from a micro-LED pixel projected onto a bundle of nanowire devices at various modulation frequencies: 25, 50, and 100 MHz, respectively.*

In Figs.2(b-d) time-domain light modulation measurements for micro-LED (in red) and nanowire (in black) devices are shown. Micro-LED measurements were taken in reflection from a plain substrate surface area, and nanowire measurements used a spectral filter to reject the pump light from the micro-LED. From our previous measurements, we estimated the cut-off modulation frequency for this micro-LED-on-CMOS board to be in the range of 36 MHz. A well-defined on-off keying of the micro-LED, and thus nanowire, is seen in Fig2(b), for the modulation frequency of 25 MHz. From further measurements shown in Figs. 2(c-d) it is clear that, although beyond the micro-LED 3-dB bandwidth, the InP nanowire devices follow the measured temporal envelope of the pump source at 50 and 100 MHz. These measurements, currently CMOS driver board limited, show the basic principle of micro-LED-on-CMOS modulation of arrayed nanowires and should be capable of further improvement since InGaN micro-LEDs have modulation bandwidths of up to 100's MHz [5], and the literature shows nanowire devices modulated in the GHz range [6].

4. Conclusion

The presented method of optical excitation of nanowire devices using individually addressable micro-LED-on-CMOS arrays enables the independent optical pumping of multiple nanowires at >MHz modulation rates. This technique, in combination with heterogeneous assembly methods, allows the fabrication of scalable systems with arrays of active components on-chip, exactly matching the spatial format of micro-LED-on-CMOS drivers. We believe that this technology will find application broadly in nanophotonics for application in areas including telecommunications, information processing, sensing and imaging.

5. References

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