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Title:

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Date:

2019-01-01

Citation:

Meng, J., Cadusch, J. J. & Crozier, K. B. (2019). Vertically stacked silicon nanowire photodetectors for spectral reconstruction. 2019 CONFERENCE ON LASERS AND ELECTRO-OPTICS (CLEO), Part F129-CLEO_SI 2019, OSA & IEEE. https://doi.org/10.1364/CLEO_SI.2019.SM4J.4.

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<https://hdl.handle.net/11343/294876>

Vertically Stacked Silicon Nanowire Photodetectors for Spectral Reconstruction

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Abstract: We experimentally demonstrate the use of vertically stacked silicon nanowire photodetectors for computational spectral reconstruction at visible wavelengths. The method is based on the photodetectors having tailored responsivity spectra, achieved by standard nanofabrication processes. © 2019 The Author(s)

OCIS codes: 220.4241, 040.5160, 120.6200.

1. Introduction

Visible-wavelength spectrometers commonly use dispersive optical components to spread light over a CCD image sensor for direct spectral readout. Although such systems can provide reliable performance, these components add bulk and expense, which limits their use for field applications. There is thus much interest in new techniques for miniature spectrometers. Previous works have demonstrated compact wavelength-multiplexed spectrometers comprising filter arrays matched to photodetector arrays [1, 2]. These previous efforts have all showed good spectral reconstruction performance, however, they all use structure in which passive spectral filters are positioned on the top of photodetectors. It would be interesting to combine these functions in one element. This is the topic of this work.

Here, we demonstrate a spectrometer chip that consists of a set of nanostructured photodetector pixels. Each pixel comprises a photodiode consisting of an array of vertically-oriented silicon nanowires (Si NWs) formed over a planar photodiode. We previously demonstrated that vertically-oriented Si NW photodetectors have responsivity spectra that can be tailored by choice of NW radius [3]. Here, each pixel of our spectrometer chip contains NWs of a certain radius and thus has a responsivity spectrum that differs from the NW photodiodes of the other pixels. This is also true for the planar photodiode of each pixel, since the NWs act as a spectral filter for the light transmitted to the planar detector. Our chip is to be used to estimate the spectrum of the light impinging upon it as follows. We measure the photocurrents from all photodiodes (NW and planar) in the chip that result from illumination by the unknown light source. These values are then input to a recursive least square (RLS, [4]) algorithm along with the photodiode responsivity spectra (measured separately). The algorithm then estimates the incident light's spectrum. We previously studied this method by simulations [5].

2. Device Fabrication



Figure 1: (a) Device schematic (b) Optical microscope image of a fabricated Si NW multi-color image with 50- μm scale bar. Inset shows an SEM image of the Si NWs forming the goddess head, with 5- μm scale bar). (c) Optical microscope and SEM image of a fabricated device. Scale bar: 100- μm . The inset shows a close view of the Si NW array poking out the SU-8 resist and coated with ITO. Scale bar: 0.5- μm

Our device is illustrated schematically as Fig. 1a. By adjusting the polarity of the applied voltage (Fig. 1a), it would be possible to switch between i). top detector (NWs) under reverse bias and the bottom detector (planar) under forward bias and ii). top detector forward biased and bottom detector reverse biased. Here the NWs contain p+, intrinsic (n-) and n+ regions with thicknesses of 0.2 μm , 2 μm and 0.5 μm , respectively. The NWs are surrounded by SU-8 photoresist. A layer of indium tin oxide (ITO, 60 nm thick) is formed on the tops of the NWs for electrical contact. The bottom photodetector is planar, comprising n+ and intrinsic regions (n-) with thicknesses of 0.5 μm and 4 μm respectively, on a p+ substrate. Each pixel has an overall extent of 100 μm \times 100 μm .

Fabrication of the device is performed as follows. The doped layers are grown epitaxially by a commercial supplier (IQE). E-beam lithography, e-beam evaporation (chromium, 40 nm) and lift-off are performed to define the etch mask for the subsequent silicon reactive ion etching (RIE) step that forms the NWs. Photolithography and RIE are then performed to make the mesa area. After that, we use SU-8 permanent epoxy to planarize the structure. This is followed by plasma etching of the SU-8 to expose the tips of the NWs. The device is completed by sputtering ITO and by lithography to make electrical contacts to the NW tips, and adding aluminum lines and contact pads.

Our Si NWs also show promising potential in color printing application. To demonstrate this, we patterned the logo of our institution via Si NWs with different radii (ranging from 60 nm to 175 nm). It can be seen that the colored regions of the goddess figure of the logo (Fig. 1b) are uniform, indicating uniformity in the NW etching.

3. Result and Discussion

Our fabricated chip (Fig. 1c) contains 24 photodetector pixels, each of which contains two photodiodes (NW and planar). The NW radii ranges from 60 nm to 175 nm with step size of 5 nm. It should be noted that these radii represent the design values employed in the e-beam lithography step. While the NW photodiodes are verified to be functional, at the time of writing their response is not stable. Here, we thus demonstrate computational spectral reconstruction using the (24) planar detectors only, whose measured responsivity spectra are shown as Fig. 2a. It can be seen that for each spectrum, the measured responsivity transitions from low to high as the wavelength increases. It can also be seen that this transition red-shifts with increasing NW radius. We next demonstrate how this allows us to perform spectral reconstruction of the incident light from the measured photocurrents of an array of N photodetectors. The photocurrent from detector k is,

$$I_k = \int R_k(\lambda)P(\lambda)d\lambda, k = 1,2, \dots, N \quad (1)$$

where $R_k(\lambda)$ denotes the responsivity spectrum of photodetector k and $P(\lambda)$ is the power spectrum of the incident light. We illuminate our spectrometer chip with light from an LED source (Thorlabs MCWHL5) that has been filtered (Thorlabs FEL0500). From the measured photocurrents of the 24 planar photodiodes, we use the RLS algorithm to reconstruct the spectrum of the incident light. The algorithm is also provided with responsivity spectra of Fig. 2a. From Fig. 2b, it can be seen that the reconstructed spectrum is in reasonable agreement with the spectrum measured by a commercial spectrometer (Ocean Optics QE-Pro), with a root-mean-square-error (RMSE) value of 0.12. In future work, we plan to reconstruct spectra using both NW and planar detector signals, as our previous simulation study [5] indicated that performance can be greatly improved when the number of photodetectors is increased.

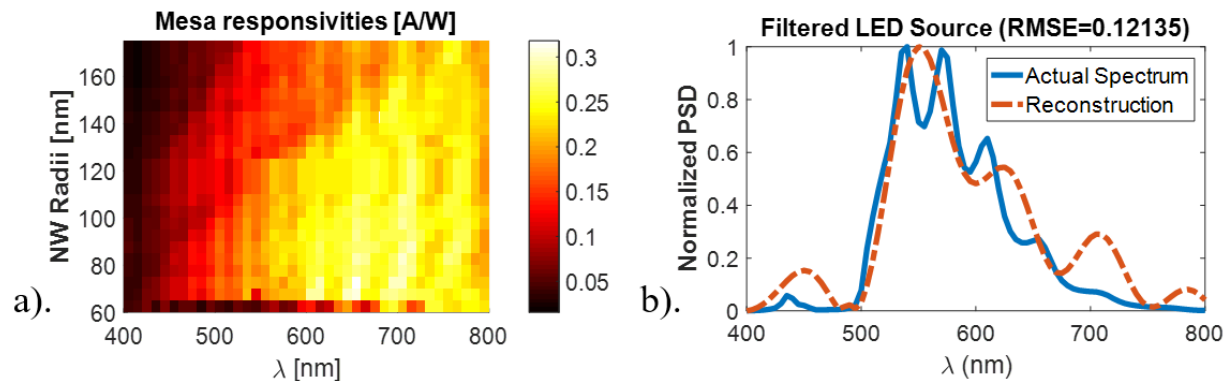


Figure 2: (a) Measured responsivity spectra of the 24 mesa planar photodetectors (b) Spectral reconstruction result

4. Acknowledgements

Supported by Palette, by Australian Research Council (LP160100959), and by VESKI. Fabrication was performed in part at the Melbourne Centre for Nanofabrication (MCN) of the Australian National Fabrication Facility (ANFF).

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