Structural Color Generation In Silicon Nanowires Enable Low-Cost Refractive Index Sensors

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ABSTRACT

Tunable color generation from vertically arranged silicon nanowires is demonstrated. The generated colors are well understood using Bragg diffraction theory. In keeping with this, vivid colors spanning the entire visible range can be produced. By combining color generation from silicon nanowires, and the abitily for the human eye to resolve small color changes, a refractive index can be realized. An index resolution of 10^{-4} is achieved by performing a simple RGB trichromatic decomposition on the collected images.

Keywords: silicon nanowires, structural colors, refractive index sensor, diffraction

1 INTRODUCTION

Structural color generation [1] has received a significant amount of attention over the past decade. It is generally well accepted that colors which are observed from various surfaces and geometeries are a result of fundamental optical interactions. These include, but are not limited to, thin-film interferences [2], diffraction grating effects [3], surface plasmon resonances [4], and interactions involving photonic crystals [5]. Recently, color generation from vertical silicon nanowires (SiNWs) arragned in square lattices has been demonstrated [6-8] in the backscattering configuration, and have been attributed to guided modes within the SiNWs coupling selectively with various substrate modes [6].

The focus of this paper is the vivid and tunable colors which can be produced by using diffraction from a square lattice of vertically arranged SiNWs. Unlike the previous studies, the generated colors are easily tuned using simple Bragg theory, allowing for controlled color generation which spans the entire visible range. In this connection, the colors are not sensitive to the diameter of the SiNWs, and depend on the lattice spacing and the angle of incidence of the incoming light. Additionally, a change in the refractive index of the medium surrounding the veritcally arranged SiNWs will produce a change in the observed color. These ideas are used to demonstrate a simple linear refractive index sensor, which has an index resolution of $5x10^{-4}$. In order to maximum the percepitble color change to the human eye, the sesnor was designed to operated in the yellow-orange region of the visible spectrum, where small changes in wavelength result in large color changes.

2 EXPERIMENTAL

2.1 SiNW Fabrication

The SiNWs were fabricated using a top down approach, which is described extensively in our previous work [8]. The SiNWs were etched in 100 µm × 100 µm square lattices, with varying lattice constants from 200 nm to 1.7 µm. The diameter and height of the SiNWs were measured to be 135 nm, and 1.1 µm repectively. Representativ top downe SEM images of three SiNW arrays are shown in Figure 1 for lattice constants of 400 nm, 800 nm, and 1200 nm.

2.2 Image Capturing and Index Sensing

A diagram of the experimental setup is shown in Figure 1. An off-the-shelf cool white LED was used to illumate the SiNW arrays. The diffracted light was captured using a microscope equipped with a 025 N.A. 5× objective, and the images were taken using a built in 5 MP camera. For the refractive index sensing experiments, Cargille refractive index fluids (Cargille USA), with values ranging from n = 1.30 to n = 1.38 were used. The index matching fluids are

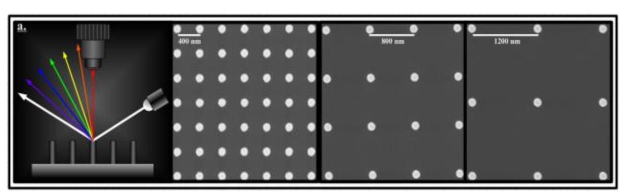

Figure 1. Schematic of experimental setup and top down SEM images for three SiNW arrays.

oil based and thus readily wet the silicon surface, penetrating into voids between the SiNW arrays.

3 RESULTS AND DISCUSSION

3.1 Color Generation

An image of colors generated from SiNWs in a bight-field setup is shown in Figure 2. In the bright-field configuration, the incident and detected light are normal to the sample. All of the arrays consist of 135 nm diamter SiNWs arranged in square lattices. In the bright-field image, the colors vary sharply for lattice spacing values between 200 and 1000 nm, and do not vary much for higher values. For larger lattice spacings, the SiNWs begin to act like individual waveguides [6,7], and as the lattice spacing decreases, strong near field coupling begins to occurr, which alters the mode properties of the array [8].

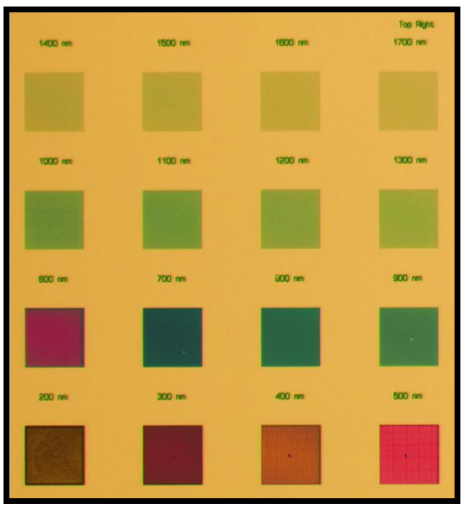

Figure 2. Bright-field image of SiNW with lattice constants varying from 200 nm to 1700 nm

To contrast the results shown above, an image of the same SiNWs arays illuminated at a 40 degree angle is shown in Figure 3. In this case colours are only observed for a certain combination of lattice spacing and illumination angle θ_i which satisifes the Bragg condition,

$$m\lambda = nd\sin\theta_i \qquad (1)$$

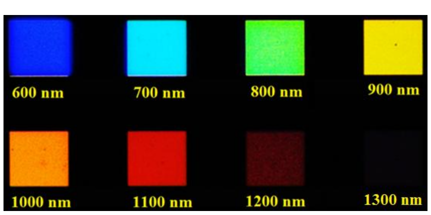

Figure 3. Diffracted colors from SiNW arrays, with lattice constants varying from 600 nm to 1300 nm, illuminated at an angle of 40 degrees.

where *m* is the diffracted order of interest, *n* is the refractive index of the surrounding medium, and *d* is the lattice spacing. That is the generated colors can be understood sufficiently well using simple diffraction theory, and hence no colors are observed for lattices spacings from 200-500 nm and from 1300-1700 nm. The background appears black since the smooth silicon surface does not diffract any light. The colors emanating from the nanowires appear very sharp and metallic like. It should be noted that in a bright-field setup color mixtures can be generated, most noteably the *d* =200 nm array which appears brown. A brown color will never be achieved in a diffraction based setup. However, by using diffraction, the same SiNW array can generate different colors of the visible spectrum ranging from blue to red. In order to confirm this, images of a SiNW array with a lattice spacing of 700 nm, which was illuminated at three different angles of 35, 50, and 65 degrees, is shown in Figure 4 below. A visibly pure red, green, and blue are easily generated from a single array. It is well accepted that human vision is based on a trichromatic response system, and the demonstrated tunable response can be used to create silicon pixels for imaging and display applications.

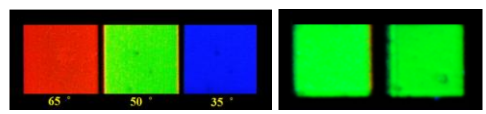

Figure 4. A single SiNW array with a lattice spacing of 700 nm illumated at three different angles (left). Two different SiNW arrays consisting of NWs with diameters of 85 nm and 200 nm (right) illuminated at the same angle.

The ability to predict the genetated color using Bragg theory does not hold when the NWs are illuminated 0 degrees to the normal. Furthermore, the generated color is sensitive to the SiNW diameter in a bright-field setup [8], whereas the generated color is insensitive to diameter when the arrays are illuminated at an angle (see Figure 4). In this connection, the observed colors resulting from diffraction, and those observed in bright-field microscopy can be used to determine the lattice spacing and diamters of fabricted SiNW arrays. The lattice constant can be calculated by illuminting the nanowires at a given angle, and once this value is known, the diameter can be ascertained from a bright-field image comparison with images of master arrays.

3.2 Refractive Index Sensing

A simple linear colorimetric refractive index sensor, which changes colour as the refractive index surrounding the NWs changes can be realized. According to equation (1), as the index changes from *n* to $n+\Delta n$, the diffracted wavelength appearing in the collection varies. In fact the variation is linear and is given by

$$\Delta\lambda = \lambda \frac{\Delta n}{n} \tag{2}$$

Here λ represent the wavelength appearing in the collection lens for a surrounding medium which has a refractive index n. Generally a given wavelength change is scaled by the initial wavelength chosen, and for the visible range, choosing a color in the red (> 630 nm) would be ideal. However the color perceived by the human eye in this region does not change much. In keeping with this, it is ideal to design the sensor to operate in the yellow-orange (~590 nm) region of the spectrum, where small wavelength changes can result in a large difference in perceived color. In terms of the RGB color space, any increase in wavelength from ~ 590 nm, should result in a decrease of stricly the G value. It should be noted that the same approach cannot be applied in the bright-field setup since one does not have a model which can predict which color should be observed and how those colors might change with refractive index.

In order to test the above design, Cargille refractive index fluids (Cargille USA) were introduced onto the SiNW arrays. Refractive index fluids with values ranging from $n = 1.30$ to $n = 1.38$ were used. A single array was setup so that a yellow hue was observed for an index value n = 1.30. Each fluid was subsequently introduced, and the corresponding image was analyzed for its RGB color content. The results of the sensing experiment are shown in Figure 5. By starting at a yellow-orange color, a larger color change can be achieved compared to when starting in the green or red as described above. Futhermore, only the G value of the RGB decompostion is varying as expected. The linear variation is naturally built into the sensor since the visible spectrum is modelled using a superposition of RGB values which vary linearly with wavelength. The theoretical refractive index detection limit of the sensor is on the order of 5×10^{-4}. Furthermore the results in Figure 5b. demonstrate that a simple approach to the design can allow for the fabrication of a linear seneor which has a large sensitivity to changes in the refractive index of the local environment.

a. b.

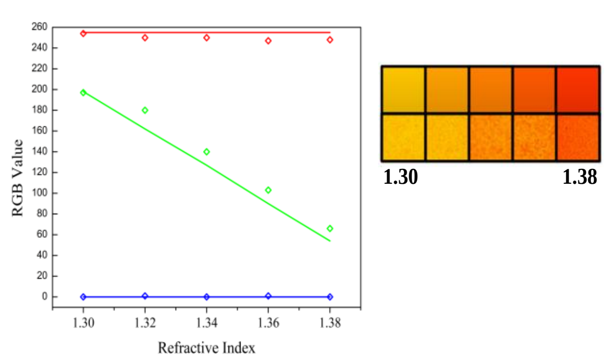

Figure 5.(a) RGB decompostion of the images taken as a function of refractive index. (b) comparison between the theoretically predicted color and the experimental color observed.

4 CONCLUSIONS

To summarize, controlled and predicatable color generation from vertical 135 nm diameter SiNWs arranged in square lattices is reported. The colors are readily understood using simple Bragg theory. In this connection the colors are well defined and do not appear dull or faded, and span the entire visible range. The controlled color generation could allow for a possible CMOS display application, or possibly a nano-monochromator-on-chip. Addtionally, by taking advantage of the relatively simple physics involved, a refractive index sensor was designed to produce a highly perceptible colour change resulting from small changes in the refractive index of the surrounding medium. The sensor uses an off-the-shelf white LED to illuminate the nanowire array, and a simple microscope to capture the images, and can potentially provide index resolutions up to 5×10^{-5}.

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