Paper ID #35781

Effective Index of Silicon Nanowires on Silicon Substrates

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Toriano graduated from Norfolk State University with his bachelor's in Electronics Engineering in the Summer of 2021. He is a lifelong competitive swimmer and water polo player and served on the Greater San Diego Science and Engineering Fair's Student Advisory Board throughout high school. His passion for science and curiosity led him to pursue a degree in engineering. In his spare time, he enjoys photography, working on cars, and going to the beach. Toriano has an interest in green technology and hopes to work within the semiconductor industry. He is currently enrolled in the graduate program at Norfolk State University where he will obtain his master's in Electronics Engineering.

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Smart City REU/RET - Effective Index of Silicon Nanowires on Silicon Substrates

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Abstract
As the demand for renewable energy increases, developing a cost-effective method of manufacturing renewable energy systems can facilitate the growth of renewable energy consumption. It is the hope that driving down the cost of renewable energy systems will allow the technology to become more accessible around the world. In solar cells, the reflected light is wasted energy. By producing silicon nanowires (SiNWs) through Metal Assisted Chemical Etching, or the MACE process, the reflectivity can be reduced to near zero. Our research highlights the process of analyzing silicon nanowire data to optimize the production of SiNWs through the MACE process. The primary focus of the research involved analyzing the effect of etching time and etchant concentration on the refractive index and the reflectivity of the SiNW samples. This was achieved by collecting Scanning Electron Microscope (SEM) images and using MATLAB, to estimate the air to silicon ratio of each sample. Also, we measured the reflectivity of the same samples. A higher air/Si ratio is expected to lower the refractive index of the SiNW layer, resulting in a low reflectivity. We concluded that the air/silicon ratio was directly proportional to H_2O_2 concentration. It was also found that the reflectivity decreased as both H_2O_2 concentration and etching time increased.

Introduction

As our cities become more connected and integrated, the need for efficient and environmentally friendly technology increases. In 2020, solar energy accounted for just 11% of all renewable energy consumption in the United States [1]. Current methods of manufacturing solar cells utilize costly anti-reflective coatings to combat silicon's natural reflectivity [2]. Silicon Nanowires (SiNWs) present a promising future for photovoltaic applications. In its natural form, the bare silicon surface reflects up to 35% of the incident light back into the atmosphere, meaning under ideal conditions, untreated solar cells made of silicon are only 65% effective at converting light into usable energy [2, 3]. Anti-reflective coatings are used to combat energy losses in solar cells. However, these coatings are costly and reduce reflectivity by a small percentage. Conversely, SiNWs have excellent light trapping and anti-reflective properties, making them significantly more effective in solar applications. SiNWs can help significantly reduce the cost associated with solar cell manufacturing, making them more accessible [2-4].

Our research is aimed at reducing reflectivity of silicon by producing silicon nanowires on the silicon substrates. We sought to reduce the 35% reflectivity to near zero through Metal Assisted Chemical Etching, or the MACE process. The MACE etching method is more efficient and economical when compared to other forms of nanowire production. This method can be applied to various areas of research that use silicon nanowires to reduce cost significantly. SiNWs are also suitable for optoelectronic devices.

Theoretical Background

Reflectance

For normal incidence, light reflected from the interface of air and a transparent film of index n_1, the reflectance is given as [4]:

$$R = \frac{(n_1 - 1)^2}{(n_1 + 1)^2}, \qquad \text{or} \qquad n_1 = \frac{1 + \sqrt{R}}{1 - \sqrt{R}} \tag{1}$$

Using equation (1), along with reflectivity data, we calculated the refractive index of SiNW using a MATLAB script with the aid of the MATLAB Image Processing Toolbox.

Experimental Methods and Materials

The MACE Process

We used the MACE process to create SiNW due to two main reasons, the low cost of materials and equipment and the suitability for large scale production [2, 4]. The method started as a two-step process where the wafer was cleaned and covered with silver (Ag), then it was immersed in a solution containing HF acid and Hydrogen peroxide (H_2O_2). Galvanic reactions occur between Ag and HF, which induce pore formation leaving wire-like structures on the surface [2-4]. It was later discovered that one single step would replace the two-step process where the wafer was directly immersed in a solution containing HF and $AgNO_3$ after the cleaning process. Many researchers have studied the various parameters that affect the SiNWs formation [2]. The MACE process is dependent on the time, temperature, and concentration of the etchant. Several SiNW samples were produced, and their micrographs were taken using SEM.

Image Processing in MATLAB

We used MATLAB to analyze the SEM images and calculated the ratios of air/Si from the binarized images, by doing a pixel count. Figure 1 shows an example of the SEM image of SiNWs which was then processed through MATLAB.

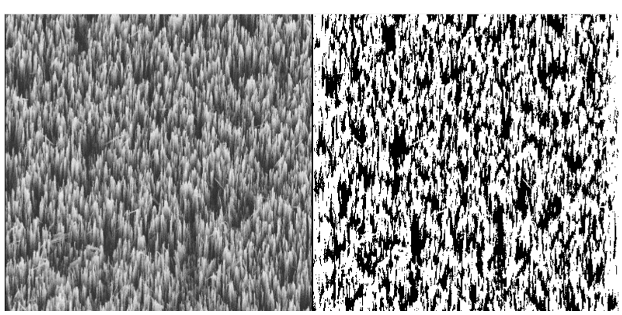

Figure 1. SEM image of SiNWs (left) and its binary image (right).

Results and Discussion

The SEM images of SiNW samples were collected using Hitachi SU800 electron microscope and analyzed for their air/silicon ratio using MATLAB. The dataset consists of SEM images of two sets of SiNW samples: (a) etched in varying concentrations of H_2O_2 at a fixed etching time of 35 minutes and (b) etched for 10 to 90 minutes, in a constant 0.2M H_2O_2. Multiple images of samples were taken at each concentration and time. The average air/silicon ratio and its standard deviation were calculated and plotted against the concentration of H_2O_2 concentration and etching time, as shown in Figure 2.

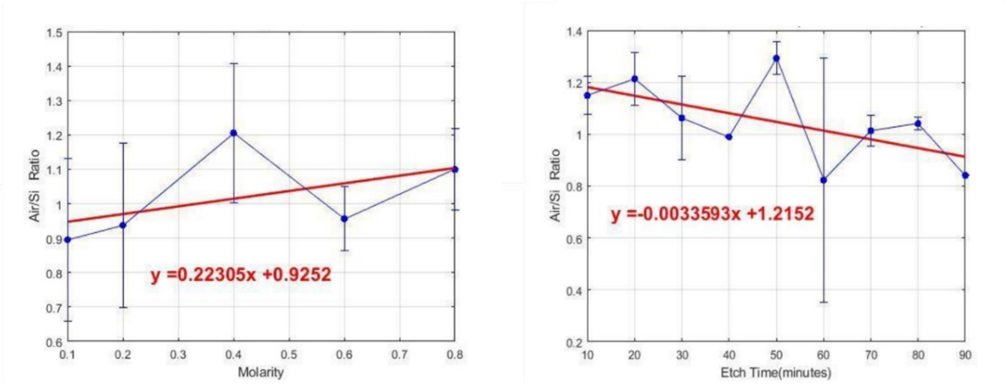

Figure 2. Air/silicon ratios for varying H_2O_2 concentration (left) and etching time (right).

From the linear best-fit graph in Figure 2, it is evident that the air/silicon ratio of the SiNW samples is directly proportional to the concentration of H_2O_2 and inversely proportional to etching time.

Reflectivity Data Analysis

The focus of this analysis is to find how the concentration of H_2O_2 and etching time used in the MACE process affect the percentage of light reflected from the SiNW samples.

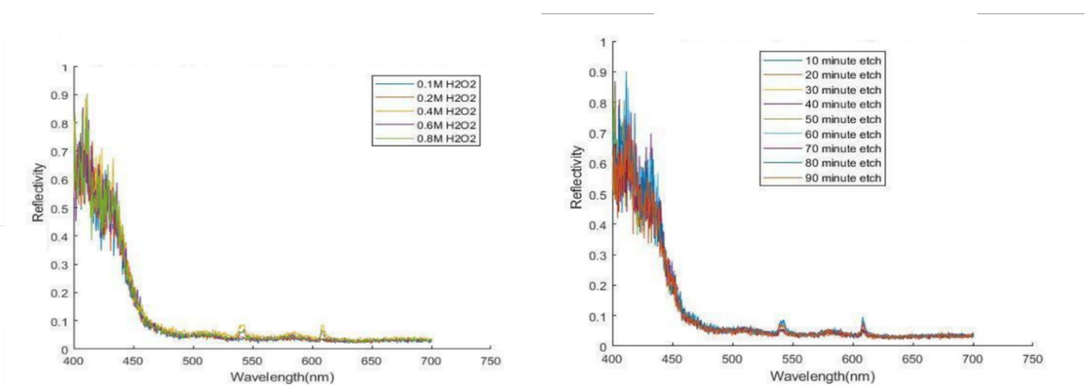

Figure 3. Reflectivity vs. wavelength for SiNW etched: (left) in varying concentrations of H_2O_2 and (right) at varying times.

For this experiment, non-polarized light was used, and the reflectivity was measured using an Ocean Optics reflectometer. The graph shown in Figure 3 compares the reflectivity versus wavelength with the same two sets of samples of SiNWs used in Figure 2. It is evident that the reflectivity decreases as H_2O_2 concentration and etching time increase; it stays relatively constant at a low value across the visible spectrum. When the etching times are even shorter, such as 20 seconds to 720 seconds, it is much easier to observe distinct changes in the reflectivity [2].

Refractive Index Analysis

The refractive index of the SiNW samples in the wavelength range between 475 nm and 700 nm was calculated using Equation (1). The graph in Figure 4 shows the refractive index in the visible spectrum for the same two sets of SiNWs samples; it is evident that the refractive index decreases as the concentration of H_2O_2 and etching time increase. However, the effective index of SiNW is significantly lower than the refractive index of the bulk silicon substrate.

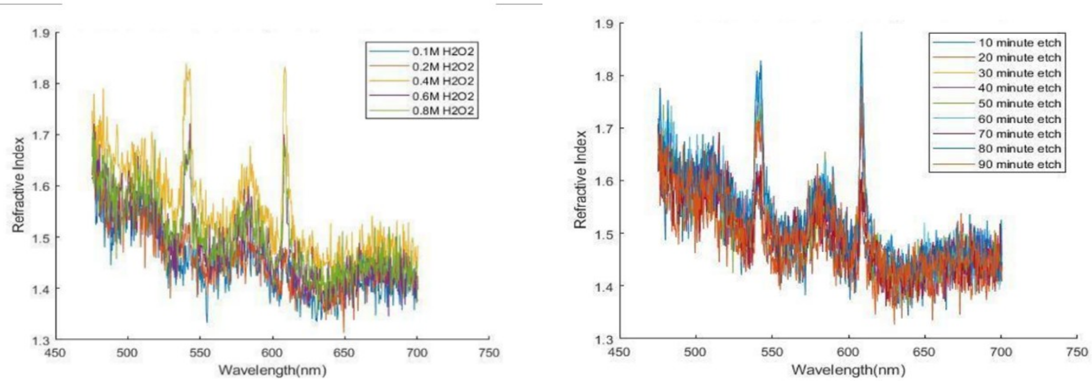

Figure 4. Refractive index vs. wavelength for SiNW etched: (left) in varying concentrations of H_2O_2 and (right) with varying etching times for the samples shown in Figures 2 and 3.

Conclusions

Our research has found that the air/silicon ratio is directly proportional to H_2O_2 concentration but inversely proportional to etching time. Reflectivity decreases as both H_2O_2 concentration and etching time increase. This is believed to be due to the reduction in the effective index of SiNW. These relationships between H_2O_2 concentration, etching time, air/silicon ratio, reflectivity, and effective refractive index can be used in an algorithm that allows the production of SiNW to be optimized for an effective refractive index and desired low reflectivity.

Acknowledgment

We want to give special thanks to Dr. Kevin Santiago, Aviha Reagan, Nelly Jerop, and Sophia Tequila for experimental data and support, and Dr. Abdinur Ali, for helping us with MATLAB. And finally, we thank the National Science Foundation for funding the REU-RET program.

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