Ain Shams University
Faculty of Engineering
Electronics Engineering and Electrical Communications

Micro-Structured Silicon for Optical Sensing Applications

A Thesis submitted in partial fulfillment of the requirements of the degree of Master of Science in Electrical Engineering (Electronics Engineering and Electrical Communications)

By:

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Bachelor of Science in Electrical Engineering

(Electronics Engineering and Electrical Communications)

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Statement

This thesis is submitted as a partial fulfillment of Master of Science in Electrical Engineering, Faculty of Engineering, Ain Shams University.

The author carried out the work included in this thesis, and no part of it has been submitted for a degree or a qualification at any other scientific entity.

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Thesis Summary

This thesis aims to discuss the development of a silicon-based infrared blackbody source for optical sensing and spectroscopy applications that can be integrated with other system components on the same chip. The thesis studies different structures including ones based on Black Silicon (BSi), one-dimensional and two-dimensional silicon gratings, photonic crystals, and plasmonic metal coated silicon structures aiming to achieve controllable high emissivity in selected wavelength ranges in near and mid-infrared ranges.

First, designs for integrated IR sources based on Si gratings are presented along with optical and thermal simulations. The designed structures are fabricated using Reactive Ion Etching (RIE) and their optical response and performance is assessed.

BSi is also proposed as a candidate high emissivity material for integrated IR sources. Extensive modeling of BSi is presented based on the Transfer Matrix Method (TMM) and the Effective Medium Theory (EMT) is successfully presented. This model assumes stacked layers of a certain refractive index profile and each layer is assumed to be a homogenous medium of a certain complex effective index. The reflectance of several simulated structures was compared to that obtained using the Rigorous Coupled Wave Analysis (RCWA) and compared with practical measurements. The model yields results of very good agreement specifically at longer wavelengths compared to the periodicity, and for structures of relatively larger spacing between the surface features within the period. The proposed model was used to study the impact of the geometrical parameters of BSi including the structure disorder. The reported model is very efficient in terms of computational speed and can be used to predict and optimize the performance of BSi.

Also, an integrated IR source based on BSi is presented and environmental gas sensing using this source is conducted in the mid-infrared range. The high emissivity is achieved by the highly-doped and nanostructured BSi that is etched using fluorinated plasma

at cryogenic temperature. On-chip platinum heater is used to raise the surface temperature of BSi leading to significant IR radiation. Experimental results demonstrating the detection of CO_2 using the proposed BSi source in the MIR range is presented, in addition to other gases (C_2H_4, SO_2 and N_2O) in fixed path-length gas cells paving the way for fully integrated gas sensors.

The thesis is divided into six chapters as follows:

Chapter 1:

This chapter provides a brief introduction to the motivation, objectives and major contributions, in addition to the organization of the thesis.

Chapter 2:

This chapter contains a literature review of silicon-based infrared blackbody sources and the potential of using black silicon and other types of micro-structured silicon (such as gratings and photonic crystals) as blackbody sources.

Chapter 3:

This chapter includes a study of using silicon-based one and two-dimensional gratings and photonic crystals as wavelength-selective blackbody emitters in the near and mid-infrared ranges. Different designs are proposed, and the dimensions are optimized to achieve the desired wavelength-selectivity in the target ranges. Optical and thermal simulations are provided along with practical measurements for the fabricated structures.

Chapter 4:

This chapter presents optical characterization of the scattering properties of BSi in the visible range. Also, a modeling technique of BSi based on the Transfer Matrix Method (TMM) and the Effective Medium Theory (EMT) is presented for the NIR/MIR wavelength ranges. The proposed model treats BSi as a multilayer structure where each layer is assumed to be a homogenous medium of a certain complex effective index. The results of this model are compared to practical measurements and more rigorous modeling techniques (RCWA) achieving very good agreement and very high computational efficiency.

Chapter 5:

In this chapter, gas sensing is chosen as an application that requires the use of white-sources, and the proposed designs are used for sensing gases such as CO_2 with the help of MEMS FTIR spectrometers. The feasibility of detecting CO_2 in ambient air is studied in near and mid-infrared, and CO_2 is successfully detected in free-space using a BSi based IR source and a MEMS FTIR spectrometer operating in the mid-infrared, in addition to other gases in a fixed path-length gas cell.

Chapter 6:

This chapter provides conclusions of the thesis and summarizes the achieved results, in addition to providing suggestions and recommendations for future work.

Keywords:

Black Silicon, Blackbody radiation, Effective medium theory, Diffraction gratings, Photonic crystal emitters, Integrated white-sources, Rigorous coupled wave analysis, Gas sensing.

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Ahmed Elsayed,
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