Near-Infrared Resonant Cavity Enhanced Silicon Microsphere Photodetector

Mohammed Sharif Murib*, Emre Yüce*, Oğuzhan Gürlü[†] and Ali Serpengüzel**

*Koç University, Physics Department, Microphotonics Research Laboratory,
Rumelifeneri Yolu, Sariyer, Istanbul 34450 Turkey

[†]Istanbul Technical University, Faculty of Sciences and Letters, Physics Department, Maslak,
Sariyer, Istanbul 34469 Turkey

ABSTRACT

Elastic scattering intensity calculations at 90° and 0° for the transverse electric and transverse magnetic polarized light were performed at 1200nm for a 50 μm radius and 3.5 refractive index silicon microsphere. The mode spacing between morphology dependent resonances was found to be 1.76 nm. The linewidth of the morphology dependent resonances was observed to be 0.02 nm, which leads to a quality factor on the order of 10^4 .

Keywords: RCE photodetector, Silicon, Microspheres, Morphology dependent resonances.

1. INTRODUCTION

The increase in data rates of inter-chip communication and the development of high speed fiber optic communication creates a demand for high speed photodetectors. Commercially available fast photodetectors such as Schottky photodiodes have bandwidths exceeding 200 GHz [1]. The efficiency of conventional high speed photodetectors is limited due to the thin absorption region needed for short transit times of the photocarriers [1]. A high efficiency photodetector needs to have a thick active region, which would increase the transit time of the photogenerated carriers and decrease the speed of the device [2]. For a photodetector to have a high bandwidth and high speed, the transit time of the photogenerated carriers within the depletion region must be small with a limited thickness for the absorption layer [2].

A solution to achieve an efficient high speed photodetector with a thin absorbing layer is the resonant cavity enhanced (RCE) device [3]. RCE detectors operate at high speed, and have a thin absorbing region, which would decrease the transit time of the photogenerated carriers [4]. RCE detectors detect light at the resonant wavelength of the cavity and reflect the nonresonant wavelengths [4]. The RCE photodetector consists of thin absorbing layer set within a Fabry-Perot cavity [2]. Once the device is illuminated with light and resonance condition is fulfilled, the light will interfere constructively within the cavity and the internal optical field amplitude will be enhanced [5].

Silicon based photodetectors are able to monolithically integrate detectors and receivers [6]. Si-RCE photodetectors have been shown to provide a high bandwidth-efficiency [6]. Si-RCE photodetectors have a low dark current of an order picoampere, which is an advantage of Si over III-V devices [6]. In addition to Si-RCE photodetectors communication systems, optical bus systems for ultra large scale integration (ULSI) circuits, I/O stages for system-on-a-chip (SOC) [7]. One of the greatest challenges in photonics has been to modify silicon to enhance light emission properties. Since the overwhelming majority of existing electronics is manifested in Si, it seems intuitive that one elegant approach would be to integrate Si-based photonic devices into the Si-based electronic devices.

** Corresponding author. Voice: +90 212 338 1312; Fax: +90 212 338 1547; aserpenguzel@ku.edu.tr.

On the other hand, microspheres have received increasing attention as optical microcavity resonators due to their high quality morphology dependent resonances (MDR) [8]. Silicon microspheres with their MDR's are a new paradigm for the use of silicon in optical communication applications [9].

2. CALCULATIONS

Figure1: Schematic illustration of a silicon microsphere coupled to an optical fiber placed at an impact parameter b away from the microsphere center.

The elastic light scattering calculations are based on the optical geometry shown in figure 1 [10]. The electromagnetic wave energy is trapped inside the silicon microsphere as it propagates around the inside surface by almost total internal reflection [11]. After circumnavigating the sphere, the wave returns back to its initial point in phase [11]. A periodic circumnavigation of the electromagnetic wave in the sphere manifests a series of sharp peaks as a function of size parameter [11].

Figure 2: Low resolution transverse electric (TE) polarized elastic scattering spectra at 1200 nm.

The system was modeled using the Generalized Lorenz-Mie theory [12]. Elastic scattering intensity at 90° and 0° for the transverse electric (TE) and transverse magnetic (TM) polarization was calculated for a silicon sphere of radius $50 \mu\text{m}$ and refractive index $m=3.5$ in the 1200 nm wavelength range. The mode spacing $\Delta\lambda$ between the morphology

dependent resonances of same mode number and consecutive mode order was calculated to be 1.76nm at $\lambda = 1200$ nm using $\Delta\lambda = \lambda^2 \arctan(m^2 - 1)^{1/2} / 2\pi a (m^2 - 1)^{1/2}$. The quality factor Q which gives information about the lifetime and the linewidth of the resonances was calculated by $Q = \lambda / \delta\lambda$ [13]. The absorption coefficient of silicon at 1200 nm is 0.0298 cm^{-1} , which corresponds to an absorption length of 33 cm, which is greater than the perimeter of the silicon sphere.

Figure 3: High resolution transverse electric (TE) polarized elastic scattering spectra at 1200nm.

Figure 4: Low resolution transverse magnetic (TM) polarized elastic scattering spectra at 1200nm.

Figure 2 shows the low resolution transverse electric (TE) polarized and figure 3 shows the high resolution (TE) polarized elastic scattering intensity in the 1200 nm respectively. The upper curve in figure 2 and figure 3 shows the elastic scattering intensity calculated for forward scattering at 0° (transmission), and the lower curve shows the elastic scattering calculated for channel dropping at 90° . Figure 4 shows the low resolution transverse magnetic (TM) polarized and figure 5 shows the high resolution TM polarized elastic scattering intensity in the 1200 nm region, respectively. The upper curve in figures (4) and (5) shows the transmitted intensity (elastic scattering at 0°) and the lower curve shows the channel dropping (elastic scattering at 90°), respectively.

Figure 5: High resolution transverse magnetic (TM) polarized elastic scattering spectra at 1200nm.

In the TE and TM polarized spectra the mode spacing ($\Delta\lambda$) is 1.76 nm which correlates well with the optical size of the microsphere. The linewidth ($\delta\lambda$) of the morphology dependent resonances shown in figures (3) and (5) is 0.02 nm, which corresponds to a quality factor Q of order 10^5 . Due to the presence of multiple sets of transverse modes with different radial mode order (l), a multimode behavior is observed [14]. The transmission is not suitable for signal monitoring as the dips are only 3% of the maximum transmission intensity. On the other hand, the elastic scattering at 90° has a larger dynamic range of about 41% of the maximum elastic scattering intensity, which leads to a relatively large interchannel crosstalk suppression [15].

3. CONCLUSIONS

Theoretical calculations for elastic light scattering from a $50\ \mu\text{m}$ and refractive index 3.5 silicon microsphere were presented and analyzed in the 1200 nm region. The mode spacing between MDRs with consecutive mode orders was observed to be 1.76 nm. The full width half maximum of MDRs was found to be 0.02 nm, which corresponds to a quality factor of 10^5 . The transmission signal is not suitable for signal monitoring, while the 90° elastic scattering has a larger dynamic range, which is suitable for crosstalk suppression between channels. The transverse electric and transverse magnetic polarized morphology dependent resonances of the microsphere can be used separately with the use of a polarizer. The 90° elastic scattering light can be accumulated using a high numerical aperture lens and measured using an InGaAs photodetector. The transmitted intensity can be measured using an optical multi-meter. The photocurrent can be measured using a current meter inserted in series with the sphere and a voltage supply. All in all, silicon microsphere can be used as an RCE photodetector and due to its high refractive index, it is possible to use smaller sized spheres, which would decrease the relative optical depth of the absorbing layer.

4. ACKNOWLEDGMENTS

We would like to acknowledge the partial support of this research by the EC Grant Nos. FP6-IST-003887 NEMO, FP6-IST-511616 PHOREMOST and TUBITAK Grant No. EEEAG-106E215.

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