Nonlinear Optical Functions in Crystalline and Amorphous Silicon-on-Insulator Nanowires

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Abstract: Silicon-on-Insulator nanowires provide an excellent platform for nonlinear optical functions in spite of the two-photon absorption at telecom wavelengths. Work on both crystalline and amorphous silicon nanowires is reviewed, in the wavelength range of 1.5 to 2.5 µm.

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1. Introduction

The high nonlinear index of silicon, combined with the high confinement in silicon-on-insulator (SOI) nanowires due to its high linear index have made the silicon-on-insulator platform an excellent platform for nonlinear optical functions and all-optical signal processing at low power. However, at telecom wavelengths crystalline silicon suffers, as a result of the two-photon absorption process (TPA), from extensive nonlinear absorption. This translates in a poor nonlinear figure of merit for crystalline silicon, defined as the ratio of the nonlinear refraction to the nonlinear absorption.

The TPA-problem is obviously absent for photon energies below half the bandgap of silicon and therefore SOI-nanowires are ideally suited for nonlinear optical functions in the wavelength range beyond 2.2 µm. In the first part of this paper our recent work in this field is summarized.

At telecom wavelengths one can mitigate the TPA-problem by using silicon only for confinement and by using a cladding material as nonlinear material. This is the approach taken in Silicon-Organic-Hybrid (SOH) waveguides, whereby a strongly nonlinear optical polymer is filling the gap of a slotted waveguide. With this approach advanced all-optical signal processing functions have been demonstrated [1,2]. A technological problem associated with this is that it is very challenging to make slotted waveguides with low linear loss.

Another approach is to replace crystalline silicon by amorphous silicon as the nanowire material. This replacement has little impact on the linear properties but improves the nonlinear figure of merit considerably. Our work in this field is summarized in the second part of this paper.

2. Crystalline silicon-on-insulator nanowires at wavelengths beyond 2 µm.

Not only is a silicon nanowire a unique waveguide for strong nonlinear optical effects, but the high index contrast also allows to engineer the dispersion – by choosing the dimensions of the waveguide cross-section appropriately - so as to achieve unique phase matching properties for four-wave mixing processes in the short-wave infrared [3]. This approach has allowed to demonstrate strong modulation instability as well as very high parametric gain (> 40 dB gain in a 2 cm long waveguide) [4], supercontinuum generation [5,6], and wavelength conversion from 2.5 µm down to telecom wavelengths and vice versa [7]. It has also allowed to demonstrate a widely tunable Optical Parametric Oscillator by embedding the silicon chip into a fiber ring cavity [8].

3. Hydrogenated amorphous silicon-on-insulators nanowires at telecom wavelengths

Amorphous hydrogenated silicon (a-Si:H) photonic wires are considered to be a good alternative for the standard crystalline silicon-on-insulator photonic wires. a-Si:H layers can be deposited at relatively low temperatures by means of Plasma Enhanced Chemical Vapour Deposition and thus be back-end deposited on a finished CMOS wafer. Several integrated photonic components based on the amorphous silicon platform, including high Q resonators, Mach-Zehnder interferometers and low-loss (3.6 dB/cm) single mode photonic wires have been demonstrated [9].

At telecom wavelengths the nonlinear refractive index turns out to be higher than that of crystalline silicon and its nonlinear absorption is lower, resulting in a figure of merit about 4 times higher than that of c-Si [10]. This has allowed to demonstrate useful nonlinear functions at telecom wavelengths including 26 dB parametric gain in a 1.1 cm long waveguide [11,12] and optical waveform sampling at 320 Gb/s [13].

An issue with a-Si:H is that it is not stable under high intensity photon illumination [14]. This effect is assumed to be related to the Staebler-Wronski effect in a-Si solar cells. However the amorphous silicon can be fully regenerated by thermal annealing at 200°C. Work is underway to see whether the material properties of a-Si:H can be optimized with respect to this degradation problem.

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