Self Phase Modulation in Highly Nonlinear Hydrogenated Amorphous Silicon

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***Abstract*— We study self phase modulation in submicron amorphous silicon-on-insulator waveguides. We extract both the real and imaginary part of the nonlinear parameter γ from a 1 cm long waveguide with a cross-section of 500x220nm^2. The real and imaginary part of the nonlinear parameter are found to be 767W^{-1}m^{-1} and 28W^{-1}m^{-1} respectively. The figure of merit (FOM) is found to be 3.6 times larger then the FOM in crystalline silicon (c-Si).**

***Index Terms*— Nonlinear optics, Amorphous silicon, Self phase modulation**

I. Introduction

Nonlinear optics in silicon-on-insulator (SOI) waveguides has been thoroughly studied in the last decade [1]. The high linear refractive index of silicon allows for waveguides with sub wavelength dimensions. The high intensity obtained by these small cross-sections combined with the high nonlinearity [2] of crystalline silicon allows for a very high nonlinear parameter. Wavelength conversion, supercontinuum generation and cross-phase modulation have been demonstrated in these waveguides [3,4,5] at very low power levels. However the large nonlinear absorption through two photon absorption limits the operation of these devices at the telecom wavelengths. A lot of research has been done on other materials which have less or no two photon absorption such as chalcogenide glasses [6]. Recently, SOI hybrid slot waveguides have been demonstrated by using a polymer cladding as the nonlinear material [7].

In this article deposited amorphous silicon (a-Si) is proposed as a core nonlinear material. The use of low loss a-Si:H waveguides has several advantages [8]. Low-loss amorphous silicon waveguides can be fabricated using complementary-metal-oxide-semiconductor compatible technology and have the potential of low-cost mass production. The amorphous silicon thin film layer can be deposited with a thickness of choice. To achieve phase matching the dispersion of a-Si:H waveguides can thereby be tuned by both the height and the width of the deposited waveguides. In this paper the SPM of short pulses is studied both in amorphous and crystalline silicon waveguides.

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II. Amorphous and Crystalline Silicon

Photonic wire waveguides were fabricated both in a-Si:H and crystalline silicon. First, 220 nm of a-Si:H was deposited using a low temperature Plasma Enhanced chemical Vapor Deposition process on top of 1950 nm of high-density plasma oxide. Waveguides of varying lengths (0.6 to 6cm in length) were fabricated using 193 nm optical lithography and dry etching [9] . Using similar a fabrication process, the same patterns were defined in crystalline SOI wafer with 220 nm of silicon and 2000 nm buried oxide. The waveguides were interfaced to an optical fiber using grating couplers. The cross-section of both waveguides was 500x220nm^2.

III. Experimental Results

Both the linear and nonlinear parameters are extracted from the crystalline and amorphous silicon waveguides. These waveguides have the same cross sections and varying lengths. The fiber-to-fiber loss was measured for different lengths (0.6 cm to 6cm) of waveguides. The linear waveguide loss of the a-Si wires was found to be 3.6dB/cm and the incoupling loss was determined to be -7dB at each grating coupler. For the c-Si the waveguide loss was determined to be 2.2dB/cm whereas the incoupling loss was -6dB. The nonlinear absorption was obtained by measuring the transmission for 4ps pulses generated by a picosecond laser source. When solving the differential equation governing the linear and nonlinear absorption it is found that the inverse of the transmission is linear as a function of the power [9] in the low power regime

$$\frac{1}{T} = \exp(\alpha L)\, L_{eff}\, 2im(\gamma)P + \exp(\alpha L)$$

However At high powers the free carriers generated by the nonlinear absorption can no longer be neglected. By extracting the slope of the curve the nonlinear absorption is determined for 1cm long waveguides. The imaginary part of γ is found to be $54W^{-1}m^{-1}$ and $28W^{-1}m^{-1}$ for the crystalline and amorphous silicon respectively. The inverse of the transmission of the 1cm a-Si waveguide as a function of the peak input power can be seen on Fig. 1.

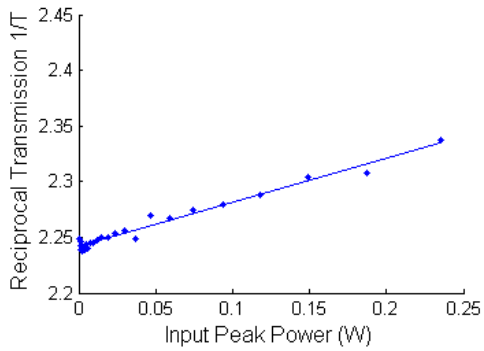

Figure 1: The reciprocal transmission in function of the input peak power of a 1 cm a-Si waveguide

We extracted the real part of the nonlinear parameter from the signature of the SPM [1, 10] spectrum as function of the input power. The signature reveals the phase shift experienced by the input pulse. The phase shift, a function of the input power, is fitted to a model describing the pulse propagation in a non-linear semi-conductor waveguide by including the effect of free carriers [1]. The simulation and measurement of the output spectra of the 4ps pulse after propagating through a 1cm a-Si are shown in Fig. 2 and 3. A *sech* pulse with a FWHM pulse width of 4ps is taken as the input pulse in the simulations. The remaining asymmetry in the experimental output spectrum is most likely caused by the asymmetry of the input pulse [10].

The fit revealed a value of $405W^{-1}m^{-1}$ in c-Si silicon and $767W^{-1}m^{-1}$ in a-Si for the real part of the nonlinear parameter. The values obtained for the crystalline waveguide are in good agreement with literature [1].

IV. Discussion

Both the imaginary and real part of the nonlinear parameter γ are extracted from 1cm long crystalline and amorphous waveguides. Using these parameters the Figure of Merit (FOM) [1] can be calculated as follows

$$FOM = \frac{Re(\gamma)}{4\pi Im(\gamma)}$$

We obtained a FOM of 0.59 and 2.1 for c-Si and a-Si waveguides respectively. The FOM of the a-Si:H silicon is about 3.6 times higher than the FOM of c-Si. Using such a highly nonlinear material other devices such as Kerr-nonlinear directional coupler can be constructed [1].

V. Conclusion

The self phase modulation of short optical pulses is studied. Both the linear and nonlinear parameters are extracted for amorphous and crystalline waveguides. The FOM of the amorphous waveguide is found to be 2.1 and thus to be 3.6 times larger than the one in c-Si.

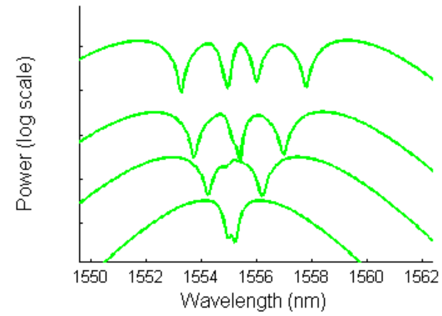

Figure 2: The simulated SPM spectrum with the fitted parameters in the 1cm a-Si wavgeuide for input peak power of 1.4, 2.9, 4.6 and 7.3W.

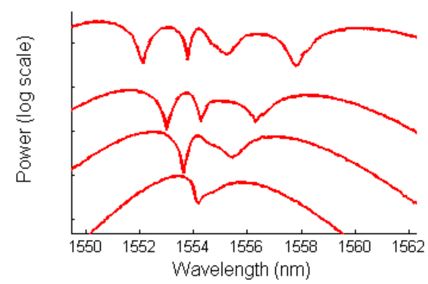

Figure 3:The experimental outputspectrum of the 4ps pulse in a 1cm a-Si waveguide for input peak power of 1.4, 2.9, 4.6 and 7.3W.

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