Nonlinear Characterization of Laser Processed Polysilicon Waveguides for Integrated Photonics

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Abstract: Polycrystalline silicon offers the full complement of functionality required for integrated optoelectronic systems, including nonlinear optical processing. Here we report low loss laser-crystallized polycrystalline silicon waveguides with nonlinear coefficients equivalent to those of crystalline silicon.

Polycrystalline silicon (poly-Si) waveguides manufactured by laser annealing of deposited amorphous materials has become a popular approach to develop integrated photonic systems using more flexible production methods than those of single crystal materials [1,2]. Despite its transmission losses being higher than other deposited materials such as hydrogenated amorphous silicon [3] and silicon nitride [4], poly-Si maintains favorable electronic properties, opening a route for the convergence of photonic and electronic systems. Here we report CMOS compatible, low temperature, poly-Si waveguides with losses sufficiently low to allow for nonlinear characterization [5]. The nonlinear coefficients are shown to be comparable to those of crystalline Si, expanding the optical functionality of the poly-Si waveguide systems to include all-optical processing applications.

To fabricate the samples, a 4 µm silica layer is grown on a standard Si wafer to provide an optically isolating buffer between the waveguides and substrate. A 400 nm amorphous silicon film is then deposited by hot-wire chemical vapor deposition (HWCVD) using a silane (SiH_4) precursor and a substrate temperature of 320 °C. Conventional electron-beam lithography and plasma-etching techniques are then used to define waveguides with a width of 3 µm. Localized laser crystallization is carried out using a 532 nm CW laser using the arrangement shown in Figure 1. Samples are mounted on micro-precision computer-controlled X/Y stages and held in place with a vacuum clamp. A white light source and CCD camera are used for precise positioning and in-situ monitoring of the crystallization process. Following optimization, crystallization was carried out with a stage scan speed of 0.1 mm/s and an incident laser power of 285 mW. The beam is focused by a 10× (0.25 NA) objective to give a spot diameter of 5 µm. The goal is to completely melt and recrystallize the waveguide, with the scan speed being adjusted to maximize the grain growth and achieve the lowest losses.

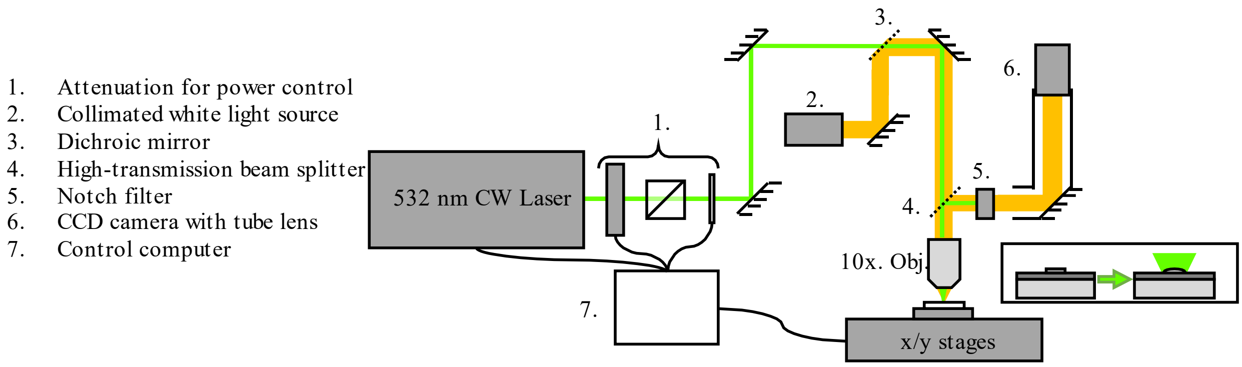

Figure 1. Laser writing setup to produce the low temperature poly-Si waveguides. Inset: Schematic showing reshaping during crystallization.

Following laser crystallization, the material quality is assessed before optical characterization begins. This is done nondestructively, firstly qualitatively by optical microscopy to check for material damage and surface quality, and secondly via micro-Raman spectroscopy. As the material is completely melted, the waveguides reshape under surface tension, as shown in the inset in Figure 1. When checking the waveguide's surface after processing, there should be no damage which would disrupt optical transmission and the surface should look completely smooth. Top-down optical microscope images of a waveguide before and after crystallization are shown in Figure 2a-b. For the Raman spectroscopy, the excitation laser is focused to a 1 µm spot diameter, and measurements are taken on both the waveguide and the amorphous bulk material. The Raman spectra of both are shown in Figure 2c. The Gaussian Raman peak for crystalline Si is centered at 520 cm^{-1} and has a width of Γ_c = 2.7 cm^{-1} (FWHM), while the poly-Si waveguide reveals a peak with Γ_p = 2.72 cm^{-1} centered at 517.4 cm^{-1}. While the width values are in strong agreement, indicating locally monocrystalline material, there is a difference in the peak position of 2.5 cm^{-1}. This is attributed to residual material strain from the annealing process due to the difference in thermal expansion coefficients of the silicon waveguide and silica substrate.

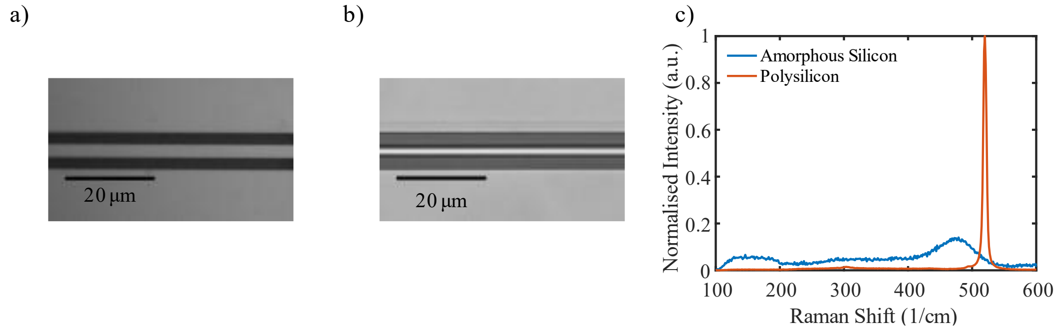

Figure 2. a) Optical microscope image of etched amorphous silicon strips. b) Microscope image of the annealed waveguide. c) Raman spectra of amorphous silicon and laser crystallized polysilicon.

The optical quality of the poly-Si waveguides is determined by cutback transmission measurements. The sample is mounted on a high-precision 3-axis stage, and CW 1550 nm laser light is coupled to the waveguides using a 60× 0.85 NA objective. At the output facet, the light is collimated by a 40× 0.6 NA objective. Both input and output facets are imaged using infrared cameras, to ensure optimal coupling. A pinhole is then used to eliminate excess light scattered from the surface and substrate, isolating the coupled mode. Optical power is measured before the input objective, and after the isolating pinhole, and from these measurements the total transmission loss is calculated. Waveguides were measured with propagation losses of 4.0 dB cm^{-1} (Waveguide 1) and 2.7 dB cm^{-1} (Waveguide 2), and respective total coupling losses of 25.8 dB and 31.2 dB.

To measure the nonlinear response of the waveguides, the CW laser is replaced with a 1540 nm, 40 MHz, 750 fs pulsed laser. Nonlinear absorption measurements are taken at a range of powers on Waveguide 1. The input and output average powers are measured. By fitting the resulting saturation curve in Figure 3b the two-photon absorption coefficient $\beta_{TPA} = 9\times10^{-12}$ m W^{-1} is calculated, based on the known linear loss, and calculated effective area from mode simulations in Comsol. Following these measurements, the output light is fiber coupled into an optical spectrum analyzer to measure the spectral broadening due to self-phase modulation. Fitting the resulting spectra (Figure 3c) with the nonlinear Schrödinger equation gives an estimated Kerr coefficient $n_2 = 4\times10^{-18}$ m^2W^{-1}. Both are close to the literature values for crystalline silicon ($\beta_{TPA} = 4.5\text{-}9\times10^{-12}$ m W^{-1}, $n_2 = 4.3\text{-}6\times10^{-18}$ m^2W^{-1}), indicating a high material quality suitable for photonics applications in multi-layered systems.

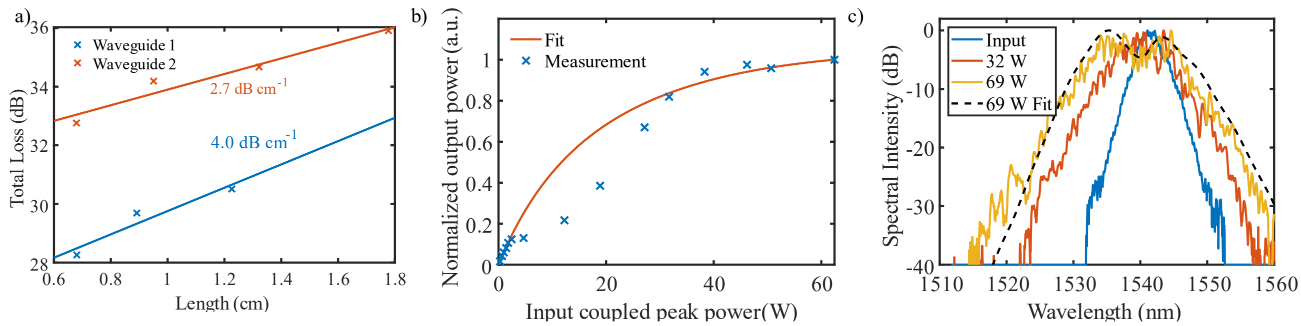

Figure 3. a) Cutback measurement of linear loss at 1550 nm. b) Nonlinear transmission saturates due to two-photon absorption (TPA). Measurements on Waveguide 1. c) Output spectra at different input peak pulse powers compared to input pulse, showing spectral broadening due to self-phase modulation (SPM). Measurements on Waveguide 1.

In summary, we have produced low temperature deposited poly-Si waveguides suitable for multi-layer integration with photonic or electronic systems. To the best of our knowledge, we report the lowest recorded loss in such a material, which has enabled the first demonstration of nonlinear transmission, opening a route for additional functionality in multi-layer architectures [6].

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