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# A Deuterium-Passivated Amorphous Silicon Platform for Stable Integrated Nonlinear Optics

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**Abstract:** We report a method to create amorphous silicon waveguides passivated with deuterium and demonstrate stability under moderate continuous-wave power. The waveguides have nonlinear properties comparable to hydrogenated amorphous silicon.

**OCIS codes:** 130.3130, 130.4310, 130.5990

## 1. Introduction

Several material platforms have emerged for realizing efficient optical Kerr nonlinearity in photonic integrated circuits. The ideal platform has a high optical nonlinearity ( $\gamma$ ), low linear and nonlinear losses, and is compatible with existing complementary metal-oxide semiconductor (CMOS) fabrication. Crystalline silicon has a large nonlinearity but suffers from large two-photon absorption (TPA) at 1550 nm due to its 1.1 eV bandgap. This drawback has prompted investigations of other materials having larger bandgaps, including silicon nitride (SN), silicon-rich nitride (SRN), aluminum gallium arsenide (AlGaAs), and hydrogenated amorphous silicon (a-Si:H). However, SN has much lower  $\gamma$  [2], SRN has high linear losses [2], AlGaAs-on-insulator requires bonding to silica [3], and a-Si:H is unstable at high average powers. Apart from its instability, a-Si:H is particularly attractive as it has the highest  $\gamma$  of any CMOS-compatible material demonstrated to date [2] and has a bandgap that can be tuned by the growth conditions.

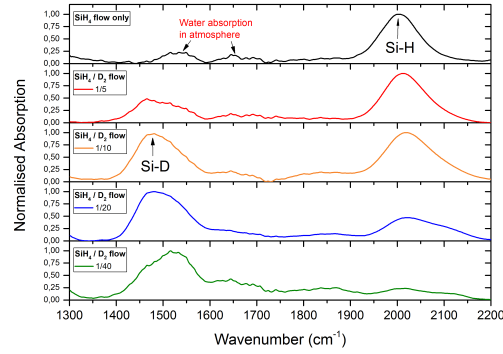
Here, we address the stability of a-Si:H by using an approach which has been successfully implemented for amorphous silicon solar cells, memory, and transistors: passivation with deuterium, creating a-Si:HD films. Waveguides fabricated from this platform have low insertion losses and a nonlinear index ( $n_2 \sim 3 \times 10^{-17} \text{ m}^2 \text{ W}^{-1}$ ) and nonlinearity ( $\gamma \sim 750 \text{ W}^{-1} \text{ m}^{-1}$ ) comparable to reported values for a-Si:H. Furthermore, the waveguides are demonstrated to be stable under moderate power continuous wave (CW) illumination for a period of over 1 hour.

## 2. Material Growth, Waveguide Fabrication and Measured Properties

The films were grown by plasma-enhanced chemical vapor deposition (PECVD) using a concurrent flow of  $\text{SiH}_4$  and  $\text{D}_2$  at 300 °C with 500 mTorr total pressure and 80 W of power at 13.56 MHz. A relatively large power was chosen to efficiently dissociate  $\text{D}_2$ . The  $\text{SiH}_4$  flow rate was either 6 or 12 sccm, while the  $\text{D}_2$  flow rate was varied between 30 and 240 sccm. By varying the ratio of the flow rates, the isotopic fraction (IF) — the ratio of the Fourier transform infrared (FTIR) signal magnitude of Si-D to the total Si-D and Si-H signal magnitude — of deuterium can be increased to nearly 100% (Fig. 1). All films were grown onto a 2.5  $\mu\text{m}$  thermally grown buried oxide on crystalline silicon wafers. Waveguides with 580 nm width were fabricated using a 250 nm thick 50% IF film, which had a measured index of 3.44 at 1550 nm. Deep ultra-violet stepper lithography and reactive ion etching were used to define the waveguides, which were top-cladded with an SU-8 polymer by spincoating.

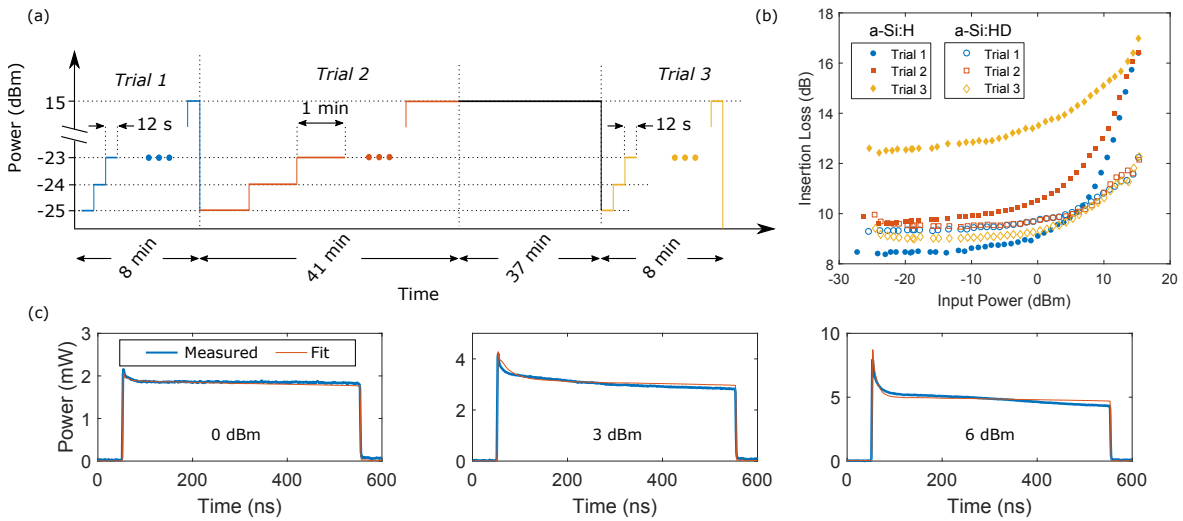
The linear propagation loss for transverse-electric polarized light measured by a cutback method is approximately 5.2 dB/cm, and the coupling loss between a 3  $\mu\text{m}$  spot size tapered fiber and the waveguide is 3.75 dB per facet. The stability was determined by measuring the power and time dependence of the insertion loss (IL) for CW illumination at 1550 nm. A 3 mm long waveguide was cycled through consecutive power sweeps as shown in Fig. 2 (a). The IL (Fig. 2 (b)) was measured three times during the cyclic testing after re-optimizing the waveguide coupling. The same measurements were done using a 6 mm long a-Si:H waveguide having a starting linear propagation loss of 4.2 dB/cm and similar coupling losses. While the a-Si:H waveguide incurs an additional IL of 4 dB due to the cycling, presumably due to Staebler-Wronski degradation, the a-Si:HD waveguide shows no significant changes.

The TPA coefficient and carrier lifetime of the a-Si:HD material were determined using the long-pulse combined pump-probe technique of Aldaya et al [1]. To accurately model the stretched-exponential carrier lifetime response present in amorphous materials [4], the right hand side of Eqn. (2) in [1] was multiplied by the unitless prefactor



**Fig. 1:** Measured FTIR spectra for films grown with different gas flow rate ratios, showing tunability of the deuterium content.

$\beta(t/\tau)^{\beta-1}$ , where  $\beta$  is a unitless stretched exponential factor with a value between 0 and 1,  $t$  is time, and  $\tau$  is the characteristic carrier lifetime. The lifetime was characterized for 500 ns long, 25% duty cycle pulses with input coupled average powers of 0, 3, and 6 dBm. The modified waveguide model of Aldaya et al was fit to the measured response using a particle swarm optimization algorithm to obtain values of the TPA coefficient, carrier lifetime, and  $\beta$ . Values of  $34 \times 10^{-12}$  m/W, 0.9 ns, and 0.48 were obtained for the TPA coefficient, carrier lifetime, and  $\beta$ , respectively. Using four-wave mixing with a CW pump and signal, we obtained a nonlinear index  $n_2 \sim 3 \times 10^{-17}$  m<sup>2</sup>/W and device nonlinearity  $\gamma \sim 750$  W<sup>-1</sup>m<sup>-1</sup>.



**Fig. 2:** (a) Power vs. time profile for the IL measurements. (b) Measured IL of a-Si:H and a-Si:HD (50% IF) waveguides. (c) Measured and fitted a-Si:HD waveguide response to 500 ns pulses.

### 3. Summary

We report a method to fabricate deuterium-passivated amorphous silicon waveguides and demonstrate that they are stable under continuous wave power. The waveguides have nonlinear and carrier dynamical properties which are comparable to those of hydrogenated amorphous silicon.

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