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Understanding radiation damage is of significant importance for devices operating in radiation-harsh environments. In this work, we present a systematic study on gamma radiation effects in amorphous silicon and silicon nitride guided wave devices. It is found that gamma radiation increases the waveguide modal effective indices by as much as $4 \times 10^{-3}$ in amorphous silicon and $5 \times 10^{-4}$ in silicon nitride at 10 Mrad dose. Our study further reveals that surface oxidation and radiation-induced densification account for the observed index change. © 2016 Optical Society of America

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High energy radiation tends to create defects in materials and thereby modify their electronic and optical properties. Mitigating radiation-induced damage associated with such defect generation is an important design consideration for devices used in outer space, near nuclear reactors, or close to particle colliders. As satellite communications and data links for next-generation particle accelerators start turning to integrated photonics solutions, [1] the demand to understand radiation-induced degradation mechanisms in photonic devices becomes critical. In crystalline optical materials such as silicon on insulator (SOI), optical property changes occur through both ionization damage and displacement damage [2]. Ionization leads to free carriers which modify refractive index and optical absorption via the plasma dispersion effect. Ionization damage also creates charged states at the Si/SiO$_2$ interface which likely accounts for the phase drift observed in SOI modulators [3]. Displacement damage results in lattice defects which impacts optical properties through local polarizability change and carrier density modulation due to trap states. Gamma radiation-induced effects in SOI have been characterized by both in-situ [4] and ex-situ [5] measurements using optical resonator devices. Besides the aforementioned bulk material structural transformations, surface oxidation was identified as a contributor to observed resonance spectral shift [5].

In this study, we focus on gamma radiation-induced effects in amorphous silicon (a-Si) and silicon nitride (SiNx) photonic devices. Both a-Si and SiNx have low optical loss near 1550 nm telecommunication wavelength [6]. For instance, SiNx waveguides with a remarkably low optical loss down to 0.045 dB/m have been demonstrated [7]. Their amorphous nature and compatibility with standard Si CMOS processing also qualify them as promising candidates for back end of line (BEOL) photonic integration [8]. Additionally, both materials exhibit large Kerr coefficients useful for nonlinear optical applications [9,10].

Radiation damage in a-Si has been investigated in electronic devices including field effect transistors [11], photodetectors [12] and solar cells [13]. In electronic devices, it was concluded that ionization damage is the primary degradation mechanism [14]. For passive photonic applications, however, bulk optical property changes in a-Si are likely dictated by atomic structural perturbations resulting from displacement defects. This is different from the case of crystalline silicon, because free carrier effects (plasma dispersion and free carrier absorption) are minimal in a-Si given its small carrier mobility. Likewise, we anticipate that displacement is the main damage mechanism in SiNx materials.

On the experimental side, radiation effects on a-Si and SiNx photonic devices have only been reported in a few recent studies. Grillanda et al. studied gamma radiation damage in a-Si resonators covered with a silicon dioxide dadding grown by chemical vapor deposition (CVD) and found minimal resonance shift up to 15 Mrad absorbed dose [15]. This observation is likely a consequence of cladding compensation as CVD silicon dioxide exhibits a negative refractive index change upon gamma ray exposure. In nitride devices, proton irradiation up to a total fluence of $\sim 10^{10}$ protons/cm$^2$ produced negligible loss change [16]. In silicon oxynitride waveguides, a large index change in the order of 0.01 was measured upon exposure to alpha radiation [17].

The present work aims to provide a precise, quantitative measurement of total dose effect of gamma irradiation on a-Si and SiNx photonic devices. Radiation-induced optical property
modifications are evaluated using micro-ring resonators. Modal effective index change of a-Si and SiNx waveguides can be calculated from the resonant peak shift whereas optical absorption increase, if any, is inferred from the Q-factor and extinction ratio change \[18\]. The irradiated a-Si and SiNx materials were also characterized by high resolution transmission electron microscopy (HRTEM), grazing incidence X-ray diffraction (XRD), and X-ray photoelectron Spectroscopy (XPS) to elucidate the underlying structural transformation mechanisms responsible for the observed optical property modifications.

Fabrication of a-Si and SiN\(_x\) resonators followed the standard Si microfabrication processes. Thin film a-Si and silicon nitride was first deposited onto silicon wafers with 3\( \mu \)m thermal oxide using plasma enhanced chemical vapor deposition (PECVD) and low pressure chemical vapor deposition (LPCVD), respectively. The SiN\(_x\) film has a refractive index of 2.1 at 1550 nm wavelength (compared to an index of 2.0 for stoichiometric Si\(_3\)N\(_4\)) and is thus silicon-rich. The a-Si devices were patterned using electron beam lithography, whereas photolithography performed on an i-line stepper was used to define the SiN\(_x\) device structures. Subsequently, the patterns were transferred to the film by reactive ion etch with Cl\(_2\) for a-Si and a mixture of CF\(_4\) and CHF\(_3\) gases for nitride. The as-fabricated a-Si waveguide has dimensions of 450 nm (width) by 250 nm (height), and SiN\(_x\) waveguide has a cross section of 800 nm \(\times\) 400 nm. Figure 1b inset shows the top view of an a-Si resonator used in our experiment.

Optical transmission spectrum of the devices was characterized on a Newport Auto Align workstation equipped with an optical vector analyzer (LUNA Technologies OVA-5000) and a built-in tunable laser. Near-infrared light was coupled in and out of the resonators through bus waveguides using tapered lens-tip fibers. In our measurements, we used the transverse electric (TE) polarization. The loaded quality factors (Q-factors) of as-fabricated a-Si and SiN\(_x\) resonators are both around 10\(^5\).

Gamma irradiation of the devices was conducted using a Co-60 source with photon energies of 1.17 MeV and 1.33 MeV. For the experiments described herein, every as-fabricated device chip was diced into two nominally identical pieces. One of them (the “sample”) was exposed to gamma irradiation while the other (the “reference”) was kept in an otherwise identical environment (i.e. at the same temperature, humidity, and lighting conditions). Post-irradiation measurements were performed with the devices mounted on a thermostat stage maintained at a constant temperature of (19.7 ± 0.2) °C. The radiation-induced resonance shift \(\Delta \lambda\) is calculated via:

\[
\Delta \lambda = \left( \lambda_0 - \lambda_{r0} \right) - \left( \lambda_1 - \lambda_{r1} \right),
\]

where \(\lambda_0\) and \(\lambda_1\) denote the resonant wavelengths of the sample before and after gamma irradiation, and \(\lambda_{r0}\) and \(\lambda_{r1}\) are the resonant wavelengths of the reference measured under identical conditions. The measured spectra from an a-Si resonator sample and its reference were presented in Fig. 1 as an example. The use of a reference chip allows us to eliminate environmental noise interfering with precise index quantification. In the experiments, we can reliably measure effective index change down to \(2 \times 10^{-6}\) in SiN\(_x\) and \(5 \times 10^{-5}\) in a-Si, with the measurement accuracy ultimately limited by temperature stability of the thermostat stage.
irradiation doses up to 20 Mrad. Standard deviation of the index measurement is less than $2 \times 10^{-4}$. Considering that the modal confinement factor in the under cladding is only about 6% and 23% in a-Si and SiN$_x$ devices, respectively, we conclude that the contribution from thermal oxide to the post-irradiation resonance shift is insignificant.

HRTEM images (shown in Fig. 2) were taken on a-Si and SiN$_x$ films before and after irradiation. The HRTEM samples were prepared by ion milling to obtain a ~20 nm thick lamella for imaging. Images before (Figs. 2a and 2c) and after (Figs. 2b and 2d) receiving 20 Mrad radiation dose do not exhibit discernable structural differences. No signs of crystallization were found after examining multiple (>10) HRTEM images. The absence of radiation-induced crystallization is further confirmed by the XRD spectra plotted in Figs. 2e and 2f, where no sharp diffraction peaks were identified after irradiation. The results exclude radiation-induced crystallization found in several amorphous material systems including a-Si [19-21] as a possible mechanism for the observed refractive index increase.

While HRTEM and XRD do not reveal clear signatures of radiation effects, XPS analysis shows surface chemistry modification as a result of gamma irradiation. Figure 3a plots the XPS spectrum of the silicon 2p peak in as-deposited a-Si film. The spectra can be deconvoluted into different Si bonding states, where the red curves correspond to Si-O bond, the blue curve are assigned to Si-Si bond and the pink curves are associated with Si-N bond. The Insets show the sums of the deconvoluted peaks, indicating good fitting quality; (b) and (d) calculated surface Si-O bond fraction for (b) a-Si and (d) SiN$_x$ samples irradiated in argon (red) and ambient air (black). The dotted lines are added as visual aids.

The impact of surface oxidation on optical resonance drift is characterized by sequentially irradiating resonator samples multiple times with 2 Mrad dose increments up to a total cumulative dose of 10 Mrad. Optical transmittance of the devices was collected before and after every irradiation session. The radiation-induced resonant wavelength shift calculated from Eq. 1 was measured in two sets of samples each containing 5 devices, and the average spectral shift $\Delta \lambda$ was used to infer the waveguide effective index change via:

$$\Delta n_{\text{eff}} = \frac{n_g \Delta \lambda}{\lambda_r},$$

where $\lambda_r$ denotes the resonant wavelength, $n_g$ represents the mode group index, and $\Delta n_{\text{eff}}$ gives the effective refractive index change of the waveguide mode. The group index $n_g$ is related to the free spectrum range in the wavelength domain (FSR, defined as the spacing between two adjacent optical resonant peaks) by:

$$n_g = \frac{2 \lambda_r^2}{\text{FSR} \cdot L},$$

where $L$ is the roundtrip length of the optical resonator. The radiation-induced index change in a-Si and SiN$_x$ measured using this method are plotted in Fig. 4. The error bars in Fig. 4 take into account the experimental uncertainty due to both temperature fluctuations and sample-to-sample variations. In Fig. 4b, the error bars are small ($< 10^{-5}$) and thus hardly visible from the plot. For both
a-Si and SiN$_x$, their refractive indices increase monotonically with increasing radiation dose when irradiated in argon. The index increase follows approximate linear dependences on cumulative total radiation dose in both materials. Since the possibility of radiation-induced crystallization is excluded, the observation suggests that densification or compaction of the amorphous atomic network is the likely cause of the index increase. In comparison, the index increase is retarded in devices irradiated in ambient air and plateaus beyond 6 Mrad dose in a-Si. In SiN$_x$, its refractive index drops slightly after an initial rise at 2 Mrad dose. Since silicon dioxide has a lower refractive index ($n_{SiO_2} = 1.45$) than those of a-Si ($n_{a-Si} = 3.6$) and SiN$_x$ ($n_{SiN_x} = 2.1$), the trend is attributed to a surface oxide formation which counteracts the index increase due to densification.

In summary, we quantified for the first time (to the best of our knowledge) refractive index increase in a-Si and SiN$_x$ materials induced by gamma irradiation through on-chip optical resonator characterization. No measurable changes in optical loss were observed in both materials. When the devices were irradiated in an inert (argon gas) environment, index increase in a-Si and SiN$_x$ follow approximate linear dependence on the total radiation dose attributed to radiation-induced amorphous network densification in the materials. The index increase is retarded in devices irradiated in ambient air due to the added effect of surface oxidation confirmed by our XPS analysis. The quantitative information on gamma radiation effects in a-Si and SiN$_x$, devices provides useful design guidelines for photonic systems operating in radiation-harsh environments.

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