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Effects of ultraviolet exposure on silicon nitride and its application in tuning passive photonic devices

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ABSTRACT

Silicon nitride films with different compositions are exposed to ultraviolet light using both an LED and a laser as light sources (with a wavelength of 244 nm and 265 nm, respectively). Collected data suggests a decrease in refractive index following the exposure, and this can be used for permanently tuning the response of passive photonic devices. The effects of ultraviolet illumination on the material are studied combining observations of the change in the response of the photonic devices and analysis of exposed films.

Keywords: Silicon Photonics, Silicon Nitride, post-fabrication trimming, ultraviolet light

1. INTRODUCTION

The silicon nitride platform can offer significant advantages compared to the traditional silicon-on-insulator platform for some integrated photonic applications.

Thanks to its wider transparency window, silicon nitride is suitable for applications in the visible and mid-infrared such as spectroscopy, biosensors, point-of-care diagnostics and quantum applications.[1–5] It is also suitable for telecommunications in the O and C bands, for wavelength conversion, and all-optical signal processing.[6–8] Other possible applications are in LIDAR and programmable photonics.[9, 10]

Silicon nitride presents a high Kerr nonlinear response. Unlike silicon, the loss due to two-photon absorption is negligible and this enables operation at higher power levels.[11]

This material can be deposited at lower temperature (<400°C) by plasma-enhanced chemical vapour deposition (PECVD) or at higher temperature by low-pressure chemical vapour deposition (LPCVD). The first is preferred for integration with materials that are sensitive to temperature, but LPCVD deposited layers have lower optical losses especially in the near infrared. The refractive index of PECVD silicon nitride can be tuned between 1.8 and 3.1 during deposition by varying the silicon to nitrogen ratio (an increase in the silicon content corresponds to a higher refractive index), which makes this platform particularly flexible.[12]

The main drawbacks of this platform are the larger footprint of the waveguides due the lower refractive index contrast with silicon dioxide, and the impossibility of obtaining optical modulation through charge carriers because of its dielectric properties.

The refractive index of silicon nitride can also be tuned post-fabrication, thanks to its sensitivity to ultraviolet light. The effect of ultraviolet light has been investigated in the past, focusing on different material properties that are affected by it, such as the type and concentration of dangling bonds and the stress profile.[13–16] This work will focus on the optical properties of silicon nitride exposed by ultraviolet light, and how these can be used for tuning the response of photonic devices.

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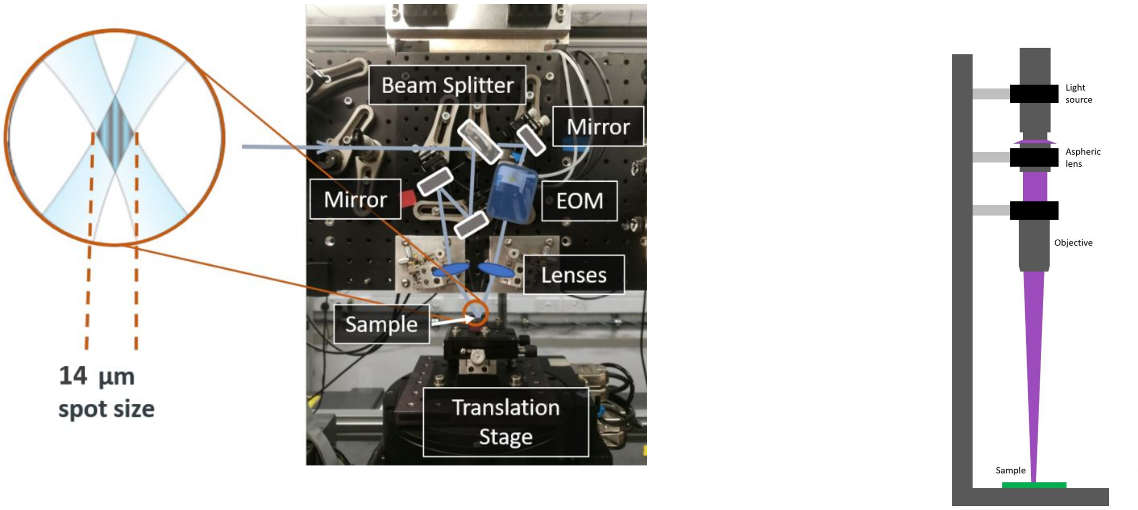
2. SETUPS

The silicon nitride samples were exposed to ultraviolet light using two different setups, one with a laser source, and one with an LED. The laser source is more suitable for small areas where high optical power density and precise alignment is required. The LED can instead expose a much larger area at once, with lower power density and it can be left on for a much longer time because it does not require any supervision and any complex positioning system.

The laser source is a frequency-doubled continuous wave argon-ion laser operating at 244 nm. The spot size used for this work is 14 µm. The position of the laser spot is controlled by an automated positioning system. The setup is built for writing Bragg gratings on chips and optical fibres by creating an interference pattern,[17] but this pattern can be avoided by using one arm of the system only or by translating the sample perpendicularly to the interference fringes so they are blurred out.

The LED light source operates at 265 nm, has a minimum output power of 24 mW and it is mounted on a much simpler and compact setup which schematic is shown on Fig. 1. If needed, the light of the LED can be collimated using a UV-coated aspheric lens and focused with an objective lens, but this causes a substantial power loss.



(a) Laser setup, as used for Bragg grating writing (the interference pattern can be avoided if not needed).

(b) LED setup.

Figure 1: Setups used for the UV exposures.

3. UV EXPOSURES

The position of the resonant wavelengths of ring resonators depends on the effective refractive index of the waveguides. Haeiwa *et al.*[18] exposed some ntirgoen-rich silicon nitride ring resonators to a UV lamp for 24 hours, proving that it is possible to change the refractive index of this material by UV exposure. We have shown that this can be done more efficiently and more accurately by using a UV laser writing system, which enables better control of the magnitude of the resonant wavelength shift by changing the values of laser fluence and total exposed area.[19] With increasing fluence and total area, the refractive index change is larger. However, its relationship with fluence is not linear, and the effect of the exposures is proportionally less strong at very high fluence. The resonances shift towards shorter wavelength, which suggests a decrease of the refractive index. This was also confirmed by ellipsometry measurements on nitrogen-rich silicon nitride samples exposed with the LED. The position of the resonances after the exposures does not stabilise immediately, meaning that the mechanism behind the refractive index change is still active when the UV light is not present. However, this stabilisation can be accelerated if the sample is heated up at temperatures below the deposition temperature.

The effect of ultraviolet exposures depends on the composition of the silicon nitride films. It is possible that the mechanism behind the refractive index change is related to the dehydrogenation of the material, given that both 244 and 265 nm light have enough photon energy to break silicon-hydrogen and nitrogen-hydrogen bonds.[20] PECVD Silicon Nitride has a higher hydrogen content than the one deposited by LPCVD, and nitrogen-rich PECVD silicon nitride has more hydrogen than the silicon-rich type. This means that Nitrogen-rich Silicon Nitride deposited by PECVD should be the most affected by the exposures. This is confirmed by ellipsometry and other spectrometric analysis carried out on different samples.

The same principle can also be applied for trimming the output of MZIs, which is dependent on the optical path length of their arms. Silicon nitride could be added as a photosensitive layer to change the response of devices built with other materials if a smaller effective index change is sufficient. Another possible application is for creating periodic gratings which can be used for optical phased arrays, avoiding etching the material.[21] Similar periodic patterns could also be used for creating Bragg gratings.

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