Buried channel waveguides in plasma-enhanced chemical vapour deposited silicon oxynitride layers on silicon substrates, formed by electron-beam irradiation

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It is shown that buried channel waveguides may be formed from a bilayer planar guide (made by plasma-enhanced chemical vapour deposition of silicon oxynitride) by bombardment with low-energy electrons. This results in an expansion of the material, and hence a decrease in the refractive index. Consequently, irradiation around a narrow stripe will induce lateral confinement. Data are presented for the electron-induced refractive index and volume changes, together with preliminary results for single-mode channel guides operating at 1.52 μm wavelength.

1. Introduction

There has recently been an upsurge in interest in processes for waveguide fabrication in amorphous multilayers on silicon substrates. The high optical quality that may often be obtained in such layers allows the construction of low-loss passive channel waveguide components, and the well-known anisotropic etch properties of silicon enables the integration of V-groove self-alignment features for accurate connection to single-mode fibres.

Generally, a three-layer waveguide construction is used, consisting of a silicon substrate, a thick low-index spacer layer and a thinner high-index guiding layer. The low-index layer is often SiO₂ and suitable high-index layer materials include the so-called 'high silica', Si₃N₄ and silicon oxynitride [1–3]. Often the high-index layer is etched into a ridge, which may subsequently be buried by an additional deposition step. However, there is also interest in processes that form a buried channel guide directly, leaving the wafer surface essentially planar. This would allow the construction of multilayer optical circuits.

The purpose of this paper is to introduce a process for the fabrication of buried channel guides in silicon oxynitride layers, which are themselves formed by plasma-enhanced chemical vapour deposition (PECVD). The method used is low-energy electron beam irradiation, which has in the past been found to cause dimensional and refractive index changes in silica [4–6] and similar changes in chalcogenide glasses [7, 8]. More recently it has been used for the fabrication of buried channel guides in silica substrates and in PECVD silica layers on silicon [9–11].
In silica the refractive index is increased, due to a reorganization of the bond angles stimulated by the energy deposited from the incident electrons rather than to local heating. Ion implantation and neutron irradiation can have a similar effect. The refractive index $n$ of a non-polar dielectric is described by the Lorentz–Lorenz law

$$n^2 = (3\varepsilon_0 + 2N\alpha)/(3\varepsilon_0 - N\alpha)$$  \hspace{1cm} (1)$$

where $N$ is the number density of polarizable oscillators in the material and $\alpha$ is their polarizability. Assuming that the result of bond reorganization is a small change in $\alpha$, we may find the corresponding change in refractive index by differentiating Equation 1

$$2n \frac{dn}{d\alpha} = \frac{9N\varepsilon_0}{(3\varepsilon_0 - N\alpha)^2}$$  \hspace{1cm} (2)$$

Since (also from Equation 1) we may obtain

$$n^2 - 1 = \frac{3N\alpha}{(3\varepsilon_0 - N\alpha)}$$

$$n^2 + 2 = \frac{9\varepsilon_0}{(3\varepsilon_0 - N\alpha)}$$  \hspace{1cm} (3)$$

Equation 2 may be written as

$$\Delta n/n = [(n^2 - 1)(n^2 + 2)/6n^2]\Delta \alpha/\alpha$$  \hspace{1cm} (4)$$

Because of the symmetry of $N$ and $\alpha$ in Equation 1, a similar equation may be found that relates changes in $n$ to changes in $N$. More often, this is expressed in terms of a change in volume $\nu$ of the material, using $\Delta N/N = -\Delta \nu/\nu$. Thus, if both changes in polarizability and volume occur simultaneously, the resulting change in refractive index is given by

$$\Delta n/n = [(n^2 - 1)(n^2 + 2)/6n^2](\Delta \alpha/\alpha - \Delta \nu/\nu)$$  \hspace{1cm} (5)$$

As can be seen, the sign and magnitude of $\Delta N$ will depend on the signs and magnitudes of the changes in both polarizability and volume, and on whether the two effects compete with each other or not. In silica, electron bombardment induces compaction. This turns out to be the dominant effect, so the refractive index increases. A channel guide may therefore be formed simply by irradiation of a narrow strip. As we now show, the opposite is the case in PECVD silicon oxynitride.

2. Waveguide fabrication

The apparatus for the experimental work is shown in Fig. 1 [9–11]. It consists essentially of a scanning electron microscope, contained in a 18 in. (45.9 cm) diameter vacuum chamber. This can be used to irradiate a sample, which is held on a cooled stage to counteract the effects of beam heating. Typically, the sample is coated with about 20 nm aluminium, which does not appreciably affect the electron penetration, but which prevents surface charging and allows measurement of the dose with a coulomb meter. The total beam current is about 0.5 mA, which results in an irradiation time of approximately 30 min for a dose of 1 C cm$^{-2}$ with a 1 cm$^2$ sample area. The beam is accelerated to 25 kV, focused magnetically to about 2 mm diameter and deflected magnetically over a 6 cm x 6 cm working area using a raster scan. At this voltage, the penetration of the electrons is estimated by Monte Carlo methods to be characterized by a Grün range of about 2.5 $\mu$m in silica [9].

The material used was an early sample of a silicon oxynitride bilayer on a silicon substrate, supplied to us by STC Technology Ltd, Harlow, UK (STL). The upper layer
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(layer A) was deposited using SiH₄, N₂, and N₂O, and had a thickness of 5 μm and a refractive index of 1.485 at λ = 0.633 μm. The lower layer (layer B) was deposited using SiH₄ and N₂O, at a thickness of 12 μm and a refractive index of 1.472. A typical buffer layer composition was 32% Si, 65% O₂, 2.4% C and 0.6% N [12]. The layer thicknesses and indices were chosen so that the upper layer acted as a planar waveguide, spaced well away from the high-index Si substrate.

Using a prism coupler, it was found that this guide supported three modes at 0.633 μm wavelength, with TE effective indices of approximately 1.485, 1.482 and 1.477. Propagation losses were determined by measuring the variation in intensity with distance of light scattered from the guide surface, using the apparatus shown in Fig. 2. This consisted of a prism coupler rig, together with a collection lens, which imaged scattered light onto a detector. Typical measured results are shown in Fig. 3 for the lowest-order mode at
\[ \lambda = 0.633 \mu m. \] Ignoring the left-hand end of the graph (which shows low loss, due to the pick-up of light scattered from the prism), and from the right-hand end (which shows high loss, due to the deliberate introduction of a surface absorber), the loss may be estimated as about 1.1 dB cm\(^{-1}\).

Silicon oxynitride monolayers with similar compositions were also supplied by STL. Using an Abbé refractometer operating at \( \lambda = 0.633 \mu m \), it was found that the refractive index of layer B decreased upon irradiation with electrons, following the curve shown in Fig. 4. This shows an approximately linear variation at low dose, saturating at high exposure. The maximum index change measured in our experiments was \( \Delta n \approx -0.006 \) at a dose of about 3 C cm\(^{-2}\). The decrease in refractive index was accompanied by an expansion of the material. This was verified by measuring the variation of the layer.

**Figure 3** Loss measurement obtained for fundamental mode of planar bilayer PECVD silicon oxynitride waveguide at \( \lambda = 0.633 \mu m \).

**Figure 4** Change in refractive index of PECVD silicon oxynitride resulting from electron beam irradiation, versus dose.
Figure 5 Refractive index change versus thickness change for PECVD silicon oxynitride after electron beam irradiation.

thickness with refractive index, using a Talystep. Fig. 5 shows that this variation is approximately linear over the same range as Fig. 4.

From Equation 5 we may estimate the index change that would follow from the volumetric change alone, assuming a maximum expansion of 50.0 nm, as

\[ \Delta n \approx -\frac{(5 \times 10^{-3})}{(5 \times 10^{-6})}(1.472^2 - 1)(1.472^2 + 2)/(6 \times 1.472) \approx -0.0055(6) \]

This should be compared with the value obtained from the straight-line intercept in Fig. 5, which shows that \( \Delta n \approx -0.0064 \) for an expansion of 50.0 nm. Since these values are so close, we may conclude that electron-induced expansion of the material is the effect dominating the index change. The small fraction of the measured value of \( \Delta n \) unaccounted for by this mechanism must therefore be due to a simultaneous slight decrease in polarizability. We can speculate that this is associated with the material moving towards a state involving a larger number of atoms with undistorted bond lengths and angles.

The electron-induced change appears to be stable at room temperature. Fig. 6 shows the results of annealing tests, for samples with an initial expansion of 50.0 nm annealed for 15 min at increasing temperatures. As can be seen, a significant reduction in the differential expansion begins to occur at around 400°C. This temperature is comparable with the transition temperature observed for electron-induced changes in silica [10], and is sufficiently high that further PECVD processing of an irradiated sample is a practical possibility.

Using an electron-induced decrease in index, it is possible to form a channel waveguide from a planar silicon oxynitride guide as shown in Fig. 7. The upper layer is simply masked with a sufficiently thick (about 0.7 μm) gold strip of suitable width, which acts as an effective barrier to electrons (Fig. 7a). Bombardment of the surrounding regions then results in the decrease in refractive index necessary for lateral confinement. This process is similar to one used previously for the fabrication of channel guides in LiNbO₃ by ion implantation (see, for example [13]). Fig. 7b shows schematically the resulting guide cross section. The index change is rather nonuniform, falling off rapidly with depth from about 2.5 μm below the surface. Furthermore, there is some infill of the guide due to sideways scatter.
A variety of channel guides was fabricated in this way, with mask widths of 5 to 12 μm and various doses. The number of modes supported at near-infrared wavelengths was found from measurements of transmission over a wide spectral range, using the apparatus shown in Fig. 8. This consisted of a white-light source and scanning monochromator, coupled to the test guide via a length of standard 8/125 μm single-mode fibre. For guide widths > 8 μm the onset of modal interference effects could typically be observed at some point between λ = 0.9 and 1.6 μm.

Fig. 9 shows the near-field intensity patterns of two 7 μm wide single-mode guides, measured at λ = 1.52 μm using a × 40 microscope objective and an infrared video camera linked to a personal computer. The upper diagram shows the result of a low fabrication dose (0.5 C cm⁻²) and the lower one shows the effect of a moderate dose (1 C cm⁻²). In the

Figure 7 Schematic of channel guide fabrication procedure: (a) irradiation and (b) approximate schematic of guide.
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![Diagram of apparatus for spectral measurement of waveguide transmission.](image)

*Figure 8* Apparatus for spectral measurement of waveguide transmission.

In the former case the beam was extremely elliptical, with an aspect ratio of about 5:1. In the latter the aspect ratio has been reduced to about 3:1. In each case the cause is weak lateral confinement, due to the small size of the electron-induced index change compared with the index difference between two layers (approximately 0.013). There is some scope for a further

![Near-field mode intensity patterns for channel guides fabricated with low (upper figure) and medium (lower figure) doses.](image)

*Figure 9* Near-field mode intensity patterns for channel guides fabricated with low (upper figure) and medium (lower figure) doses.

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reduction in the ellipticity through increased dose, but for approximately circular modes a decrease in the layer index difference will clearly be required.

Due to the short lengths of guide available, it was not possible to measure the absolute propagation loss, although at $\lambda = 0.633 \mu m$ it is likely that this will be in excess of the 1.1 dB cm$^{-1}$ quoted earlier. Some interfacial scattering was also observed near the guiding channels. However, the spectral variation of the loss was measured over the near-infrared range, again using the apparatus of Fig. 8. Fig. 10 shows typical results for a 6$\mu m$ wide guide. These have been corrected to eliminate spectral variations in light output from the monochromator and in fibre transmission, but not for variations in coupling efficiency between fibre and guide (which are likely to be considerable, despite the use of index-matching oil). OH- and NH-related absorption peaks at 1.41 and 1.52$\mu m$, originating in the PECVD material, were common to all samples tested.

3. Conclusion
Irradiation with low-energy electrons has been shown to be a simple low-temperature process for the fabrication of buried channel guides from bilayer silicon oxynitride structures. The stability of the guides thus formed has not yet been addressed in detail. However, no discernible changes in guiding properties were observed over a period of several months.

Although the results here are preliminary, it is anticipated that improvements to the optical quality of the PECVD material, and a better match between the electron-induced index change and that due to the layering, will allow the construction of low-loss guides that are directly compatible with optical fibre. Furthermore, since the guiding region is not itself irradiated, there is scope for the fabrication of additional features (e.g. slow tapers in the index of the guiding region itself) by the same method.

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References

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