Silica-on-silicon waveguides with MgF2 cladding layers paper

by Mark Finne

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***Abstract*—we report on the choice of MgF_2 as cladding layers on silica-on-silicon optical waveguides fabricated by electron beam irradiation. The deposition methods need to be chosen carefully with low temperature as not to damage the low refractive index change during fabrication process. The main consideration is that the refractive index of the cladding layer should be very close to that of silica and it have good transparency, as well as be capable of being deposited at low temperature. The thickness profile then examined using DEKTAK II surface profiler.**

Keywords—MgF_2 cladding, silica-on-silicon, optical waveguide

I. Introduction

An important requirement of all integrated optic systems is the availability of low loss waveguides. Of all the technologies described earlier, silica-on-silicon integrated optics is now the most advanced. It's simple fabrication also offers cheap processing and compatibility with established silicon-based microelectronics. It has the particular advantage that a wide range of low-loss components can be produced on large substrates. Furthermore, silica-on-silicon guides have similar parameters to those of optical fibres, allowing low coupling loss. The devices, however, are currently mainly of passive optical function [1]. The initial point of silica waveguide formation is a silicon wafer, typically 10 cm in diameter, ≈500µm thick, and of (100) orientation. It has the advantage of a high degree of planarity, ready adhesion of the deposited silica and excellent heat dissipation [2]. It has the potential to allow hybridisation of optical and electronic components onto a common substrate, and substrate crystallinity can be exploited to fabricate V-groove structures for passive alignment of optical fibres with the integrated waveguide [3].

To fabricate waveguides in silica-on-silicon, a number of different glassy layers must be deposited on the Si substrate. A uniform buffer layer of silica is first deposited to a thickness of 10-20 µm. The buffer thickness should be large enough to prevent the light from the core layer leaking into the substrate, which has a much higher index than silica. The required thickness increases as the difference in refractive index between core and cladding is reduced.

A second layer of glass (from which the core will eventually be formed) then is deposited on top of the buffer layer. The refractive index of this layer must be slightly higher than that of the buffer in order to allow light guidance. The required index difference can be achieved by doping with suitable compounds. Dopants that increase the refractive index of silica include Al_2O_3, As_2O_3, GeO_2, N_2, P_2O_5, TiO_2 and ZrO_2. Amongst these GeO_2 has attracted considerable interest because it can be used to create a relatively high index core [4]. The thickness of the core is determined by two requirements: (1) the waveguide should be single mode, and (2) coupling loss to a single mode optical fibre should be minimised. A final layer of silica is deposited above the core to produce a buried channel waveguide. It is important to ensure that the refractive index of the top cladding matches as closely as possible to the buffer layer in order to symmetrise the optical mode propagating in the core.

Electron beam irradiation can be used to fabricate low-loss channel waveguide components operating at near infrared wavelengths. Substrate absorption and OH^- contamination have been minimized, and low (≈ 0.1 dB/cm) and spectrally flat propagation losses have been obtained in material deposited by plasma enhanced chemical vapor deposition (PECVD) [8]. A number of device configurations has also been demonstrated, using a simple process based on irradiation through an electroplated Au surface mask. However, despite its ability to produce a low loss waveguide, the irradiation process is currently unproved. For example, the effect of irradiation itself has been found to be highly material-dependent. The achievable index change is also weak, the stability of the induced change is limited, and further processing after irradiation remains an issue to be solved.

In this paper we report the use of MgF_2 as cladding layers in electron beam irradiation fabricated silica on silicon waveguides.

II. CHOICES OF CLADDING LAYER ON ELECTRON BEAM FABRICATED WAVEGUIDES.

To form a practical device from an irradiated waveguide, a permanent cladding layer must be deposited over the core. The main consideration is that the refractive index of the cladding layer should be very close to that of silica. It should also have good transparency, and be capable of being deposited at low temperature. Good chemical stability and low water absorption are also necessary. In a low Δn silica-on-silicon waveguide (especially for waveguide formed by electron beam irradiation process), a thick silicate glass is used to isolate the core. The required thickness can be reduced by lowering the cladding refractive index, which at the same time increases the range of possible materials and deposition processes. However, it increases the asymmetry of the guide, and any polarization-dependence of modal properties.

Several deposition methods can be used to form the cladding layer, for example sputtering, and PECVD. However, deposition by sputtering usually is too slow. PECVD is much faster, but would require the waveguide to be subjected to a temperature of (350 ^{0}C for several hours). High temperature thermal annealing might then also be required to eliminate OH^- contamination and obtain low propagation loss. An alternative is a spin-coated, UV-cured polymer. A number of polymers with low refractive indices is available [5]. Spin-coated layers of one particular polymer, EPO-TEK 06125, were investigated, but difficulties were found with the adhesion of the layer when it had reached a thickness suitable for a cladding (10 μm). The dimensional stability of the layer was also found to be questionable. Alternatively, a number of inorganic materials is also available, Table 1 shows a list of inorganic materials with low refractive indices.

Material	**Refractive Index**
Sodium Fluoride	1.30
Magnesium Fluoride	1.39
Potassium Chloride	1.45
Calcium Fluoride	1.45
Silica	1.46

Table 1. Refractive index of inorganic materials suitable for use as a cladding layer, after reference [6]

All are potentially suitable for a cladding layer but have some drawbacks. Silica is the ideal candidate; however the high temperature deposition needed would erase the irradiation-induced changes. Potassium fluoride is not chemically stable, being extremely hygroscopic. Calcium fluoride is also chemically unstable, and its high melting temperature (1423°C) poses a major problem in any deposition process. The only realistic possibility is therefore magnesium fluoride (MgF_2), which can be deposited relatively rapidly by thermal evaporation. MgF_2 deposition is already very well-known and the facility for the process is very mature. Although it has a rather low refractive index, the results of the previous analysis suggest that any polarization effects are likely to be small.

III. MEASUREMENT OF MgF_2 CLADDING THICKNESS

Based on the analysis above, It was therefore decided to investigate the use of MgF_2 as a cladding layer. Simulations of slab waveguide structures with representative parameters were first performed to evaluate its suitability. Figure 1 shows the structure and layout of such a guide, assuming buffer, core and cladding indices of 1.458, 1.464, and 1.39 respectively and a core thickness of 5 µm. The TE mode profile obtained by solution of the standard eigenvalue equation for an asymmetric guide at λ=1.523 µm is also shown.

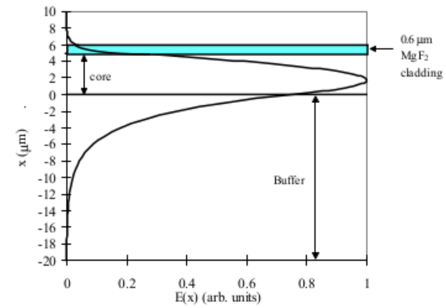

Figure 1. Geometry and mode profile of a planar silica waveguide with an MgF_2 cladding layer.

Because of the relatively large index step at the core-cladding interface, the mode profile is highly asymmetric, and the rapid decay of the evanescent field in the cladding suggest that any sensitivity to further over layers such as metal electrodes should reduce rapidly with MgF_2 thicknesses above (1 µm). This thickness can be deposited by thermal evaporation, although the sample must be heated to eliminate water of crystallization and obtain a consolidated film.

After several initial experiments, it was found to be relatively simple to deposit a 0.6 µm thick crack-free MgF_2 cladding layer on top of PECVD silica-on-silicon. The deposition temperature used was about 140-145 °C, and the evaporation time about 19 minutes. Figure 2 shows the profile of a deposited MgF_2 step, as measured by a DEKTAK II surface profiler. The average thickness is about 0.66 µm.

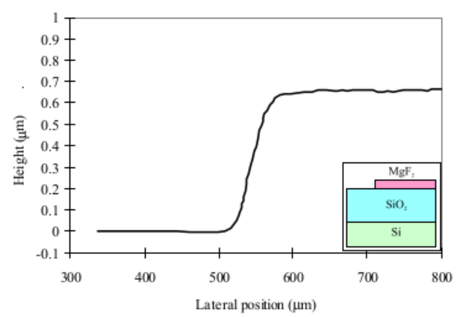

Figure 2. Thickness profile of the MgF_2 cladding, scanned from the edge of the silica layer.

Application of MgF_2 cladding layers was then investigated in Mach-Zehnder interferometric switch geometries. The Mach-Zehnder interferometer provides an elegant means of taking advantage of the thermo-optic effect. It consists of two back-to-back Y-junctions connected by two straight guide arms. The first Y-junction splits the input light into two components which travel along the straight guide and are recombined at the second Y-junction. Either or both the straight arms may have a heater to allow the relative phase of the recombining components to be altered. If the two are in phase, the guided output is high, and if they are out-of-phase, it is low.

In Mach-Zehnder interferometric switch geometries, the heater was deposited above MgF_2 by patterning a 0.1 µm thick layer of sputtered Ti metal into 50 µm wide strips fed by 4 mm wide bus bars, and a dummy electrode was placed above the unheated arm to avoid any phase or amplitude imbalance [7]. Figure 3 shows a surface profile over one arm of the waveguides, including the cladding and the Ti layer, as measured by a DEKTAK II surface profiler.

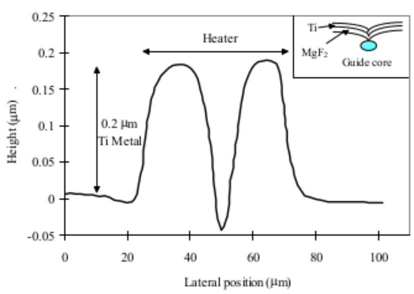

Figure 3. Surface profile scanned over one arm of an interferometer

The cladding and heater shape follow the surface profile of the guide. This shows a considerable depression at the guide center after irradiation, which falls off gradually on either side [7]. The measured heater resistance was R = 530 Ω for 4 devices in parallel. Metal strips were also placed over straight sections of waveguide for comparison purposes.

The layout of the Mach-Zehnder 1x1 single mode optical switches used to investigate thermo-optic switching in irradiated waveguides is shown in Figure 4. The device has two straight arms of 10 mm length and an additional thin film of Ti metal, to act as a heater electrode..

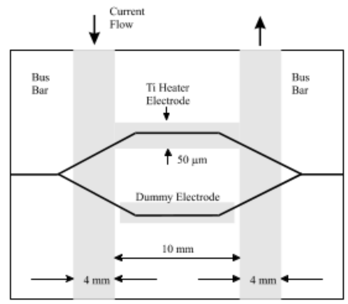

Figure 4. Layout of thermo-optic Mach-Zehnder interferometric switches

Figure 5 shows a photograph of the electrodes in the vicinity of the bus-bars. The irradiated waveguides may clearly be seen running beneath the upper heater electrode and the lower dummy.

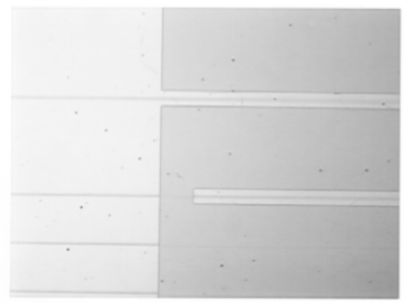

Figure 5. A photograph of the devices as shown in Figure 4.

Without a cladding layer, very large (> 25 dB) TM mode interferometer insertion losses were obtained. Losses decreased dramatically as the cladding thickness was increased, and the majority of the TE/TM loss differential was eliminated with 1 µm of MgF_2 as shown in Table 2. Any additional TE/TM differential in straight guide propagation loss or in waveguide insertion loss was then assumed to be due to polarization-dependent absorption by a metal overlay.

MgF_2 thickness (µm)	**TE/TM loss differential (dB/cm)**
0.6	1.5
1.0	0.5

Table 2. Loss parameters of waveguides and devices with different MgF_2 buffer thicknesses.

IV. Conclusion

We have reported the use of MgF_2 as cladding layer for silica-on-silicon waveguide fabricated by electron beam irradiation. Loss parameters can be reduced considerably by increasing the MgF_2 thickness layers. We have also managed to deposit thin Ti layer on top of MgF_2 as heater for further used in switching devices. Because process times and temperatures are low, this coating method avoids degradation of device performance by annealing of the irradiation induced index changes.

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