Optimisation of borophosphosilicate glass compositions for silica-on-silicon integrated optical circuits fabricated by the sol-gel process

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Indexing terms: Sol-gel processing. Integrated optoelectronics. Borosilicate glasses

Silica-on-silicon channel guide devices fabricated in sol-gel borophosphosilicate glass deposited by repetitive spin-coating and rapid thermal annealing (SC-RTA) are described. Process parameters for a wide range of glass compositions are given. The optimum performance is obtained using a borosilicate buffer layer, a phosphosilicate core and a borophosphosilicate cladding with a low melting point. Low-loss thermo-optic interferometric modulators fabricated by this process are described.

Silica-on-silicon integrated optical circuits are conventionally made from silica glasses formed by flame hydrolysis (FHD) [1] or chemical vapour deposition (CVD) [2]. The sol-gel process is an alternative; however, until recently, it has been difficult to fabricate sufficiently thick glass layers on Si substrates to obtain low loss. This problem has been overcome using repetitive spin-coating and rapid thermal annealing (SC-RTA), adjusting the RTA temperature to avoid stress-cracking [3].

The RTA temperature is reduced by introducing PO₃ and B₂O₃ dopants, so that thicker layers of sol-gel phosphosilicate glass (PSG) can be deposited than those of silica or silica-titania, and even thicker layers of borophosphosilicate glass (BPSG) can be formed. In addition, channel guides can be reflowed controllably using PSG and BPSG. A steady reduction in propagation loss has therefore been obtained, by changing the glass system from silicatitania [4] to PSG [5] and then to BPSG [6].

The PSG and BPSG guides described above have suffered two disadvantages: the core-cladding index difference has been small (Δn ≈ 5 × 10⁻⁴), and the core has been deformed by the cladding steps [5]. For example, Fig. 1a-c show oblique views of a 7μm × 6μm guide core in BPSG after repetitive ion etching, refloew and burial. In Fig. 1e the core shape (revealed by etching in buffered HF) is grossly distorted compared with Fig. 1b, due to stress during annealing. Here, we show how to avoid these problems. We first investigate the optical quality, RTA and refloew temperatures of various BPSG compositions, and then use optimised glasses to demonstrate silica-on-silicon devices.

Preparation of the BPSG sol has been described [5–7]. Tetraethylorthosilicate (TEOS) is mixed with propy-2-ol, H₂O and an HCl catalyst, and refluxed to hydrolyse on average one OR group per TEOS molecule (R = 1). The PO₃ dopant is added as a solution in propy-2-ol, together with further water and catalyst, and the solution hydrolysed to R = 2. The B₂O₃ dopant is then added as a solution in propy-2-ol, and a final dilution made to adjust the viscosity. Individual glass layers are formed by spin-coating for 40s at 2000rpm, and annealing in O₂ for 10s. The RTA temperature needed to avoid cracking is found by methods described elsewhere [3]. The refloew temperature is found as that required for full refloew of a guide core in 5min in O₂.

Fig. 2 Compositional map of sol-gel BPSG system

- a Contours of rapid thermal annealing temperature
- b Reflow temperature

BPSG sols containing up to 15molar% of PO₃ or B₂O₃ are investigated, as shown in Fig. 2a. The circles indicate the compositions assessed, together with an indication of their optical quality. We have found the B₂O₃ concentration to be limited to ≈7.5molar%, because more heavily doped sols are moisture-sensitive, yielding gels that are often cloudy after spin-coating. The likely explanation is the rapid hydrolysis of boron alkoxides [7]. Similarly, we have found that the PO₃ concentration is limited to ≈12.5molar%; although clear gels and glasses can be formed at higher levels, the glasses become opaque in high-temperature processing. Fig. 2a also shows contours of constant RTA temperature. For SiO₂, this temperature is very high (=1100°C); however, it is reduced rapidly as PO₃ or B₂O₃ is introduced.

The best results are obtained in the unshaded region of Fig. 2a, where the glasses are clear and the RTA temperature is moderate. The challenge is to exploit this window to obtain optimum guide performance, by choosing appropriate refractive indices and melt temperatures. The index variations of typical compositions have been described [6]; broadly, the effect of PO₃ is to increase the index above that of SiO₂, whereas that of B₂O₃ is to lower it. Fig. 2b shows contours of constant refloew temperature. This temperature is also reduced as the PO₃ or B₂O₃ content is increased.

Fig. 2b shows the compositions of the earlier PSG and BPSG systems. Each system uses only two different glasses. The same glasses are used as the buffer and cladding, and the core-cladding index difference is established by a 5molar% difference in PO₃ content. Because the melt temperature of the buffer is lower than that of the cladding, a pinned-base refloew can be performed. However, the high RTA temperature of the cladding is responsible for the core deformation. To minimise core deformation, a third glass (with a lower RTA temperature) is required. In addition, to maximise mode confinement, the largest possible index differences should be established between core and buffer, and core and cladding. Three-glass systems have previously been demonstrated by CVD [2]. Fig. 2b shows a suitable sol-gel system. For the buffer, we have used the most heavily-doped composition of pure borosilicate glass (BSG) practical, containing 7.5molar% B₂O₃, and for the core, the most heavily-doped PSG, containing 10molar% PO₃. For the cladding, the requirements of low index and low RTA temperature are
incompatible; we have compromised the former aspect in favour of the latter, using BPSG containing 5.75mol% B₂O₃ and 6.75mol% P₂O₅. The result is an asymmetric guide, with a λ₀ of ≈1.5 × 10⁻⁸ to the buffer but only half this value to the cladding.

Fig. 1d shows the cross-section of a buried guide in this BSG/PSG/BPSG system: the core deformation has all but vanished. The propagation loss at λ = 1.523μm is almost identical to that of the BPSG system (=0.2dB/cm) [6]; however, bend losses are reduced.

For example, Fig. 3 shows the variation of TE mode fibre-device-fibre insertion loss with transition length L, for 3.4cm long chips containing back-to-back sinusoidal S-bends giving a 150μm lateral offset. Shorter transitions, with tighter minimum radii, can be tolerated in the new system.

![Graph showing variation of TE mode fibre-device-fibre insertion loss with transition length L, for 3.4cm long chips containing back-to-back sinusoidal S-bends giving a 150μm lateral offset.](image)

Fig. 3 Variation of fibre-device-fibre insertion loss with minimum bend radius for back-to-back sinusoidal S-bends formed

A thick cladding is essential for thermo-optic switches, where the guided mode must be isolated from the heater electrode to avoid polarization-dependent absorption. We have used the above glasses to construct Mach-Zehnder interferometric modulators, using Y-junctions based on similar bends. With a 10μm thick buffer, a 6μm core and 10μm cladding over the core, a TE mode insertion loss of 3.5dB is achieved for an overall device length of 3.4cm. Switch-off and switch-on times of 2ms and 4ms, respectively, are achieved using ≈0.5W drive power, as shown in Fig. 4.

![Graph showing switch characteristic for thermo-optic modulator based on sol-gel BSG, PSG and BPSG](image)

Fig. 4 Switch characteristic for thermo-optic modulator based on sol-gel BSG, PSG and BPSG

For this cladding thickness, the presence of a 2000Å thick Ti electrode above the guide contribute an additional propagation loss of 2.8dB/cm for the TM mode. However, polarization-independent insertion loss is obtained with a 15μm thick cladding. Any remaining losses are ascribed mainly to bending and splitting losses, which have not yet been optimised.

In our view, these results represent the first practical demonstration of a sol-gel silica-on-silicon device as distinct from a simple waveguide. However, due to the low value of λ₀, these guides are still not suitable for tight bending circuits. Since the guide parameters described here appear close to the best obtainable using P₂O₅ and B₂O₃, we conclude (as have others before us) that any further increase in λ₀ requires an additional core dopant such as GeO₂.

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References


Radar cross-section computations using the parabolic equation method

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Two-way parabolic equation (PE) techniques are used to compute the radar cross-section of two-dimensional objects. A finite-difference implementation of a wide angle PE in combination with non-local boundary conditions allows fast execution times on a desktop computer. The technique is applied to scattering by a cylinder and by an idealised aircraft shape. Numerical results are in good agreement with calculations using other methods.

The forward parabolic equation (PE) has been used extensively to solve tropospheric radiowave propagation problems [1, 2]. Here we apply two-way PE techniques to 2-D scattering problems.

For a field component ψ, we remove the fast phase variation in x by solving for the reduced function w(x, z) = ψ(x, z exp(-ikx)), where k is the free space wave number. After factoring the scalar wave equation we obtain the PE for the field propagating in the positive x direction:

\[ \frac{\partial w(x, z)}{\partial x} = -ik \left( 1 - \sqrt{1 + \frac{1}{k^2} \frac{\partial^2}{\partial z^2}} \right) w(x, z) \]

The solution of eqn. 1 can be marched in range with split-step Fourier or finite-difference algorithms. Here we have chosen the finite-difference option, which allows more flexibility for the modelling of the object boundary and easier truncation of the computational domain.

The accuracy of the numerical solution depends on the choice of rational approximation for the square root operator in eqn. 1. A narrow angle version of the PE based on a linear expansion, which is adequate for angles up to ~15° from the horizontal has been presented in [3]. Another possibility is the Cauchy approximation: