Low loss achieved in sol-gel based silica-on-silicon integrated optics using borophosphosilicate glass

R.R.A. Sym, V. Schneider, W. Huang and A.S. Holmes

Polarisation-independent propagation losses of 0.26dB/cm are reported for near-infrared silica-on-silicon channel guides formed using sol-gel borophosphosilicate glass deposited by repetitive spin coating and rapid thermal annealing. The low loss is ascribed to a reduction in process temperature, which has allowed a total glass thickness of 30µm. The use of two dopants allows the glass viscosity to be adjusted independently of its refractive index, simplifying reflow and burial.

Silica-on-silicon is now established as the premier candidate for chip life density integrated optical circuits. Several processes have been developed for passive device fabrication, including flame hydroxyl deposition (FHD) [1], chemical vapour deposition (CVD) [2] and plasma-enhanced chemical vapour deposition (PECVD) [3]. These processes all involve topographic guides formed by embedding shaped silica channels in a silica surround. To obtain low coupling loss to singlemode fibres, the cores are large (6 – 8µm) and weakly confining (Δn = 0.25 – 0.75%), although smaller, higher Δn systems are now being investigated for complex circuits [1]. A thick (>12µm) buffer layer is used to minimise substrate losses, and a thick cladding to reduce attenuation from electrodes in thermo-optic devices. Low scattering is achieved by using homogeneous glasses, and by smoothing core sidewalls using a reflow step. Finally, absorption is minimised by careful choice of dopant (the most common being TiO₂) [1], GeO₂ [1] and P₂O₅ [2, 3] and by elimination of O-H contamination.

An alternative process has been developed at Imperial College, London [4–7], based on the repetitive spin coating and rapid ther-
naturally, the reduction in process temperature is limited by the behaviour of heavily-doped PSG. This material is well known to be unstable [8], becoming opaque during high temperature processing. We have found the maximum practical P,O content to be ~10 mol% (~9 wt% P) [7].

A further reduction in the reflow temperature can be achieved by using B,O, in addition to P,O [8]. However, although B,O, and P,O both increase the glass viscosity, they have opposite effects on the refractive index. If the buffer, core and cladding glasses are chosen carefully, for example, as silica, PSG and BPSG, respectively, the melt temperatures of the layers can be arranged in descending order, allowing the cladding to be reflowed over the core without significant remelting.

![Fig. 2 Variation of refractive index with composition for sol-gel phosphate-silicate and borosilicate glass](image)

Using a sol-gel based BPSG process, we have found the same general behaviour. This is illustrated in Table 3 (which shows melt temperature against composition, for a 5min reflow) and Fig. 2 (which shows refractive index against composition). However, a further advantage is that the RTA temperature is again reduced. For example, for 5mol% B,O, and 10mol% P,O, annealing can be performed at 800°C. One explanation is that both P,O and B,O increase the thermal expansion coefficient of SiO [9], reducing the stress caused by thermal mismatch with the Si substrate. The combined effect is that thicker (>30m) layers of glasses with improved wetting characteristics can be deposited with sol-gel BPSG than with either PSG or TeO,SiO, giving reduced optical loss.

**Table 3:** Temperatures required for full reflow in 5min, for different BPSG compositions

<table>
<thead>
<tr>
<th>mol% B,O</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1265°C</td>
<td>1150°C</td>
<td>1000°C</td>
<td>1050°C</td>
</tr>
<tr>
<td>5</td>
<td>1175°C</td>
<td>1050°C</td>
<td>950°C</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1125°C</td>
<td>1000°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>1125°C</td>
<td>925°C</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The BPSG sol used in our experiments was prepared using a recipe adapted from one previously described [6, 7]. Briefly, tetraethylorthosilicate (TEOS) was mixed with propan-2-ol, H,O and an HCl catalyst, and refluxed to hydrolyse on average one OR group per TEOS molecule (R = 1). The P,O dopant was added as a solution in propan-2-ol, together with further water and catalyst, and the solution is hydrolysed to R = 2. The B,O dopant was then added as a solution in propan-2-ol, and the solution refluxed again. A final dilution was carried out to adjust the viscosity as required.

Using this sol, films were built up by repetitive spin coating and rapid thermal annealing, and completed biarrays were consolidated at 1000°C to obtain uniform glass properties [4]. After reactive ion etching to form 7μm wide cores, the guides were reflowed using rapid thermal processing, and buried beneath a thick cladding. A final consolidation step was then employed. Optical characteristics were then measured by standard fibre butt-coupling methods.

Propagation losses at λ = 1.525μm were 0.2dB/cm, independent of polarization. This figure is the lowest reported to date for sol-gel silica-on-silicon technology, and represent a considerable advance over our previous efforts.

![Fig. 3 Insertion loss against wavelength for straight waveguides in sol-gel borophosphosilicate glass](image)

Since all sol-gel reactions proceed by condensation polymerisation, O-H absorption at λ = 1.39μm arising from residual water contamination might be expected in sol-gel glasses. For BPSG, this is not the case; we have found that spectrally flat performance is obtained without further dehydration, as demonstrated by the insertion loss measurement of a 3.5cm guide length shown in Fig. 3.

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Electronics Letters Online No: 1995/1230
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**References**