Development of Planar Optical Waveguides using UV-Patternable Hybrid Sol-gel Coating

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ABSTRACT - Ridge and buried channel waveguides were fabricated on different substrates such as SiO_2-on-Si, Si, glass wafers and Printed Circuit Boards by a sol-gel processing together with a photolithography process using photopatternable hybrid sol-gel materials. Thick sol-gel films of up to 100 microns were developed using a modified sol-gel process and ridge waveguides with vertical smooth sidewalls were obtained. The refractive index of the coatings can be varied in a large range by modifying some components of the sol-gel precursor while the coating quality was retained.

Keywords: Hybrid sol-gel, Coatings, Channel waveguides, Photolithography

1 BACKGROUND

There is increasing demand for high-density integration of optical and electronic components, in which planar optical waveguide technology will play an important role. The planar waveguides employed in this technology are developed with different methods including Physical Vapour Deposition (PVD), Chemical vapour Deposition (CVD), Sol-gel, and polymer coatings as well as ion implantation in glass substrates. Sol-gel processing has been proven an effective route in producing high quality coatings, and therefore, a practical approach in fabricating planar waveguide devices at low cost [1-3]. The high compatibility of sol-gel coating with different kinds of substrate materials and the ability to modify their refractive index make them an ideal candidate for optical interconnection on silicon wafer and on Printed Circuit Boards (PCBs).

Organic-Inorganic hybrid sol-gel (HSG) materials, also called “ORMOSIL's”- organically modified silicates or “ORMOCER”- organically modified ceramic, are new functional materials and their properties are similar to glasses (usually transparent in visible and NIR ranges) [4-5]. Specially, UV-patternable hybrid sol-gel (UVPHSG) glasses are those HSG that have one or more photosensitive organic groups, usually with unsaturated C=C bonds, which can be polymerized upon UV light irradiation and have been approved as good material for thick waveguide development [6-10]. By multicoating of layers with different refractive indices, surface, channel and buried waveguides can be developed readily with a photomask and a conventional UV mask aligner.

In this project, we have developed a modified sol-gel fabrication process by introducing reflux reaction and evaporation processes in addition to the hydrolysis process. Thick layers of up to 25 μm were prepared using one spin-coating step. The coating surface is very smooth with an average roughness smaller than 1 nm measured by atomic force microscope (AFM). With these specifications, the UV-patternable coatings are suitable for being used in developing planar waveguides for wafer level and PCB level optical waveguide interconnection. Other passive optical devices such as optical splitter and couplers, multimode interferometer (MMI) devices, arrayed waveguide gratings (AWGs), as well as thermal-optical switches can be fabricated with these coatings.

2 OBJECTIVE

The objective of the present project was to develop a process for UV patternable sol-gel optical waveguides on different substrate materials such as Si wafer, glass, ceramic as well as PC boards for interchip optical interconnection. The scope of this report is to show the planar waveguide development and characterisation by the photo-imprintable hybrid sol-gel material.

3 METHODOLOGY

3.1 Fabrication of patternable sol-gel coatings

The hybrid organic-inorganic coating solution is mainly based on MEMO-methcryloxylpropyltrimethoxysilane, which has a methacrylate group with a non-saturated bond (C=C double bond) that enable it to be polymerisable upon UV light irradiation. Other materials include metal-organic alkoxide-zirconium n-propoxide, methacrylic acid (MAA) and n-propanol. The detail of the coating and process development was reported in another technical report. The film thickness can be controlled by either changing the preparation process or applying multicoating technique.

3.2 Sol-gel waveguides development

Coating solutions were applied on different substrates including silicon, silica-on-silicon and glass wafers as well as PC boards by using the spin coating technique. To form a waveguide structure, 500 nm SiO_2 on Si wafer were used as substrates for the hybrid coating. Photolithography processes were conducted in a 10k-grade clean-room environment to exclude particles from the deposition films. The flowchart in Fig. 1 shows the waveguide fabrication process for the sol-gel UV patternable coating.

An EV620 UV mask aligner with a UV light intensity of 25 mW/cm^2 was employed to polymerize the coating through openings of a photomask. After photo imprinting, samples were developed with 1-propanol or ethanol. A final thermal treatment was done at 160-180^oC for under N_2 gas flow. In order to avoid surface cracking caused by the shrinking of sol-gel component at high temperature, very low heating and cooling processes were used.

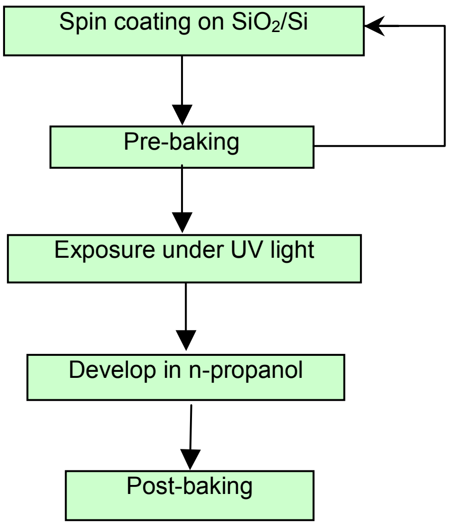

Fig. 1. Flowchart for sol-gel waveguides development.

3.3 Types of planar waveguides

Different structures of planar waveguides can be developed with multicoating process. Fig. 2 illustrates four different kinds of waveguides. These waveguides can be fabricated using coatings with different refractive indices or using a pre-coated low refractive index layer, for example, SiO_2 layer.

3.4 Characterisations

Coating surface roughness was studied by AFM. The patterns developed were observed using both an optical microscope and scanning electron microscope (SEM). The three-dimension pictures of the developed coating profile were measured with both a Taylor-Hobson stylus profilometer (for a large area) and SEM (for a small area).

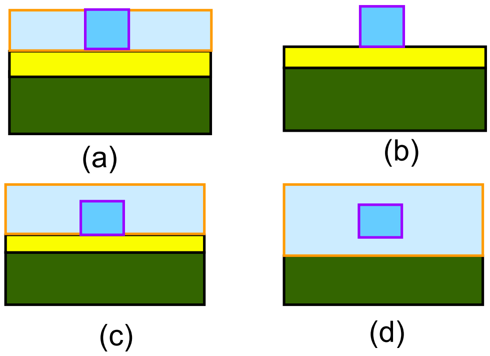

Fig. 2. Different sol-gel waveguides structures. (a), Surface waveguide; (b), Ridge waveguide; (c), Non-symmetry buried waveguide; (d), Symmetry buried waveguide.

Stylus profilometer was also used to measure the coating thickness. Refractive index for the coatings was measured with both a prism coupling equipment and a spectral ellipsometer. For layers thicker than 4 µm, only the prism coupling method was used. Waveguide coupling measurement was realized using a 632.8 nm He-Ne laser with direct fiber coupling or microscope objective coupling method.

4 RESULTS

4.1 Coating thickness

According to the application requirements, the thickness of the hybrid sol-gel coatings can be adjusted in a wide range from less than 1 to several tens µm. For a layer less than 2 µm, the evaporation step depicted in Fig. 1 is not necessary. While for even thinner layer, the coating solution should be diluted with 1-propanol for the desired thickness. Depending on the solvent content in the coating solution, coating thickness can be varied from 3 µm to 20 µm with one single spin coating step. Thicker layers can be realized using multi-coating process and a ten-minute prebaking at 110^oC is applied after each coating step. With a coating solution that produce a coating with thickness of about 10 µm for a single layer, a thickness of 36 µm was obtained with 4 spin-coating layers.

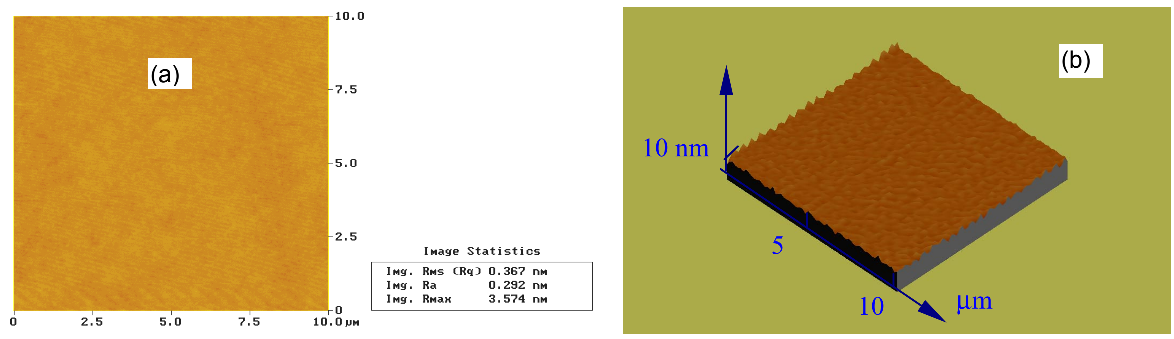

Fig. 3. 2D (a) and 3D (b) AFM surface morphology pictures of an 8 µm thick hybrid sol-gel coating.

4.2 Surface morphology

Coating surface morphology was analyzed using an AFM. Results obtained from a 10 µm thick hybrid coating are shown in Figs. 3(a) and 3(b). Fig. 3(a) is a 2D picture of an area of 10 x 10 μm^2 on the coating surface, which shows an average surface roughness RMS of 0.367 nm and a maximum roughness value of about 3.6 nm. These values are comparable with the best coatings prepared using commercial BCB (Benzocyclobutene) or polyimide photosensitive coatings. The 3-D surface morphology depicted in Fig. 3(b) is shown with a Z scale of 10 nm. These pictures reveal a very smooth coating surface of optical quality obtained by the modified sol-gel process.

4.3 Microscopic pictures of the developed patterns

Fig. 4 shows optical microscope picture of a series of 10 µm channel waveguides obtained from an 8 µm thick layer. 10 µm optical channels with separations ranging from 5 to 200 µm were accurately produced. In order to obtain a more comprehensive view of the coating profile, three-dimensional plots were recorded using a profilometer. Fig. 5 shows a profile recorded of the same 8 µm coating. Series strips with widths from 10 to 200 µm were developed accurately by this process with relatively sharp walls. To get a clear view of the walls, the profile was enlarged along the vertical axis about 10 times with respect to horizontal axis. Fig. 6 shows a SEM picture of ridge waveguides of 10 µm width and 8 µm thickness developed on a 500 nm SiO_2/Si wafer. This picture shows also good pattern profiles developed from sol-gel coating.

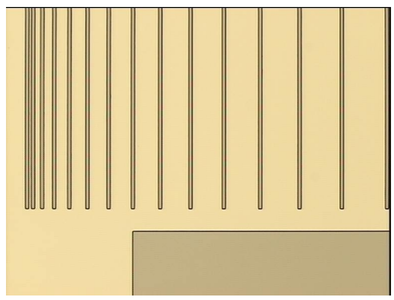

Fig. 4. Optical microscope picture of a series 10 µm strip waveguides with separations from 10 to 200 µm.

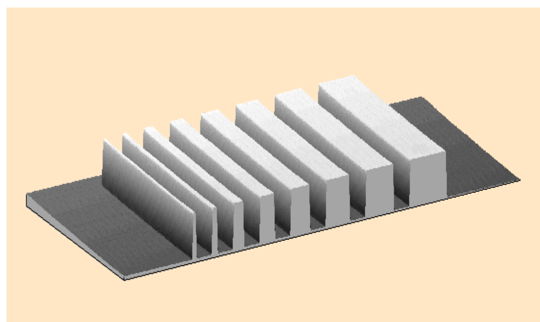

Fig. 5. 3-dimension picture of an 8-µm thick coating with widths ranging from 10 to 200 µm.

4.4 Refractive index with different treatment

Optical constant measurements were conducted on thin layers with thickness between 1 and 2 µm using both prism coupling and spectroscopic ellipsometer methods. Films with thickness larger than 4 µm can only be measured by the prism coupling technique. The refractive indexes measured by these two techniques are quite consistent. For example, for a film exposed to UV radiation for 30 min and post baked at 160°C for 30 min, the refractive index measured with 633 nm He-Ne laser is 1.516, while the fitting results from spectral ellipsometer is about 1.515 at 633 nm.

For different samples prepared using the same procedure, the refractive index is in the range between 1.513 and 1.517. Considering the precision of the measuring system, these values are very close to each other. This indicates that the reproducibility of the optical properties of the hybrid sol-gel coating is very good. This value is well above that of the SiO_2 buffer layer, for which the refractive index is 1.457. If SiO_2 or a similar material was used asbuffer and cladding layers for a buried waveguide device, the big difference inrefractive index between the core and cladding layers will result in a larger numerical aperture and enable easy optical coupling.

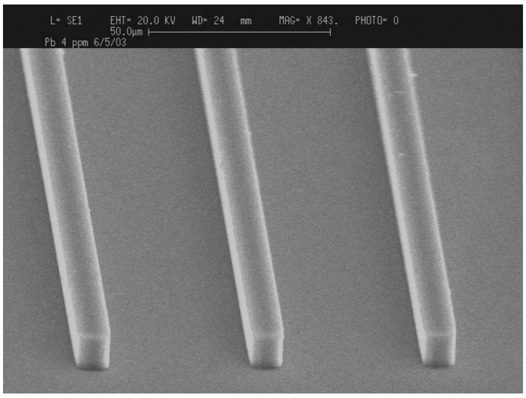

Fig. 6. SEM micrograph of a series of Hybrid sol-gel strip waveguides of 10 μm wide and 8 μm thick.

Fig. 7 shows the refractive index change as a function of the UV exposure times for a 2-mm sample with 25% zirconium precursor.

The relation between photopolymerization and thermal polymerization can be identified clearly from this figure. After 30 min of prebaking at 110°C, the refractive index of the film is about 1.498. This value increased to 1.509 when a postbake of 30 min at 160°C was applied. When irradiated with UV light, a large refractive index change was observed in the first 10 min with a Δn of 0.011. After this period, the refractive index increases slowly to about 1.513 after 20 min UV exposure (corresponding to $\Delta n=0.015$). With even longer exposure time, the refractive index keeps practically constant with no further significant increase. This indicates that the photopolymerization is essentially complete after about 20 min for the thin layer. For thick layers, a longer UV exposure time is needed.

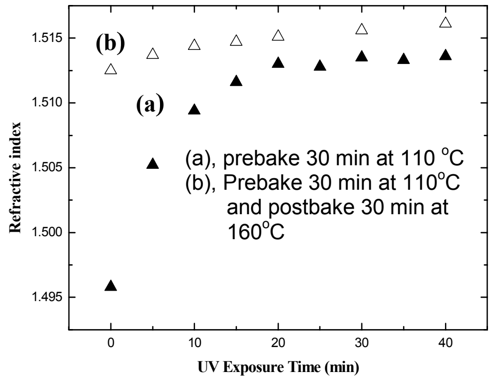

Fig. 7. Refractive index change as a function of UV-exposure time. Samples were prebaked at 110°C for 30 min (a) and further post-baked at 160°C for 30 min (b).

30 min is usually enough for a 10 μm-thick layer. When the films were postbaked at 160°C for 30 min, much smaller refractive index change was observed as a function of the irradiation time, as shown in Fig. 7. For the non UV exposed film, the refractive index at 633 nm increases to about 1.512, which shows a Δn of 0.014 compared to the prebaked sample. For those samples exposed to UV light for 5 to 40 min, only a the hybrid sol-gel material can be realized by both photo-irradiation and thermal treatment. Both processes are equally efficient for solidifying the films.

Direct coupling of the He-Ne laser to the developed channel waveguides was studied by both fiber coupling and microscope objective coupling techniques. The results will be reported later.

5 CONCLUSION

Planar optical waveguide on thick hybrid sol-gel coating was developed with a photomask and a conventional mask-aligner. High precision and high aspect ratio were obtained on the developed waveguides.

High quality Photolithography-developed patterns were studied by different techniques including optical microscope, atomic force microscope, scanning electron microscope and profilometer. AFM results reveal a very smooth coating surface of optical quality with an average surface roughness of 0.367 nm for an area of 10 μm x 10 μm. Complex patterns with high aspect ratio were revealed by both 3-D profilometer and scanning electron microscope.

Refractive index measurements by prism coupling and spectral ellipsometer indicate high reproducibility of coating properties prepared by this procedure. The measured refractive index is well about the silica buffer layer, which ensure a big numerical aperture for waveguide coupling. The changes of refractive index with respect to different treatments make it possible to design all-sol-gel buried waveguides by changing treatment process for different layers. The results shown in this work indicate that both thermal treatment and photo-irradiation are effective routes to polymerize and densify the sol-gel films.

6 INDUSTRIAL SIGNFICANCE

Sol-gel method was proven to be an appropriate and cost effective process for planar waveguides development. The high compatibility of sol-gel coating on different kinds of substrate materials and the ability to modify the refractive index make them an ideal candidate for optical interconnection on silicon wafer and on PCBs.

The technique developed in this project can be used to fabricate thick hybrid sol-gel films by spin-coating method. This process will attract interests from the optoelectronic industry for component integration and packaging. The thick films developed through this work will find possible applications in the ONFIG-related optoelectric projects in Singapore for planar waveguide devices. FINISAR Singapore has shown interest in developing hybrid sol-gel coatings with high aspect ratio.

The high precision patterning process has attracted attentions from other industry as well. Hewlett-Packard Singapore has shown great interest to introduce the sol-gel coating in its new generation print head fabrication process. The feasibility study is still on going.

In a word, the hybrid sol-gel coating cannot only be used in fabricating planar waveguides based devices, but in various other industrial applications. The technology developed in this project is a highly value-added and cost-effective technology.

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