Hybrid Sol-gel Integrated Optics on High Index Substrate for Heterogeneous Integration

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Material synthesis, device design and fabrication of integrated optics using multi-layer hybrid sol-gel on high index substrate are presented. The results show the potential of hybrid sol-gel for heterogeneous integration with semiconductors.

Keywords: hybrid organic-inorganic sol-gel, guided-wave optics, integrated optics

Introduction

Heterogeneous integration is the enabling approach for the development of complex, low cost integrated optoelectronic components and subsystems. Hybrid organic-inorganic materials have great potential for integrated optics [1]. With the introduction of an organic chain containing C=C bond, the hybrid sol-gels show properties similar to glass and polymers [2,3]. These include photopatternability, low optical loss and long-time stability. In addition, their planarization and masking capabilities make them attractive for semiconductor processing and integration [4]. One major limitation for the integration of hybrid sol-gels with semiconductors is their low refractive index. Thick, crack-free, low index buffer layer is used to solve this problem. In this paper, the hybrid multi-layer sol-gel waveguide and integrated optics on high index semiconductor is reported. The material synthesis based on methacryloxypropyl trimethoxysilane (MAPTMS) as well as device fabrication are presented and characterized.

Waveguide structure design

Prior to fabrication, the design and optimisation of ridge and buried sol-gel waveguides on high index Si substrate is conducted by effective index as well as BPM using BPM-CAD software. We consider the materials with refractive indices of \( n_{\text{cladding}} = 1.467 \) and \( n_{\text{core}} = 1.501 \). In order to eliminate any radiation into the substrate, the thickness of the lower cladding layer should be greater than 10 \( \mu \text{m} \). The core size is chosen as 3 \( \mu \text{m} \) thick, and the top cladding is chosen as 6 \( \mu \text{m} \) thick (about 3 \( \mu \text{m} \) above the top of the core). The wavelength used for simulation is 1550 nm. The mode profile of the structure is shown in Fig. 1. Symmetric mode with good confinement is obtained.

![Fig. 1 Buried waveguide mode profile by simulation with BPM_CAD](image-url)
The mode coupling between the waveguide and a single mode fiber is of great importance and can be evaluated from the overlap filed integral of Equation (1).

\[
C = \frac{\left( \iint E_i^*(x,y) \times E_e(x,y) dxdy \right)^2}{\left( \iint E_i^*(x,y) \times E_i(x,y) dxdy \right) \times \left( \iint E_e^*(x,y) \times E_e(x,y) dxdy \right)}
\]  

(1)

With a \( \Delta n \) of 0.033 between the core and cladding material, the waveguide has a NA of \( \sim 0.31 \). Considering a conventional single mode fiber a coupling loss of about 2 dB is calculated for a simple butt-coupling technique.

**Material synthesis and buried waveguide fabrication**

Two kinds of hybrid sol-gel materials based on MAPTMS with different refractive indices are synthesized for the core and the cladding layers. The Zirconium Propyloxide (ZPO) - MAPTMS is chosen for the core for its high refractive index. A molar ratio of 78 : 22 between MAPTMS and ZPO is chosen, which gives a refractive index of 1.501 at 1550 nm. 1.3 wt.% of IRGACURE 1800 (CIBA) is added as photoinitiator for UV-polymerization of the methacryloxy group. The lower and upper claddings are a mixture of MAPTMS and tetraethoxysilane (TEOS). The two precursors are hydrolysed separately with different concentrations of hydrochloric acid (0.01M for MAPTMS and 0.1 M for TEOS) prior to their mixing. The molar ratio between MAPTMS and TEOS is 65 : 35, which gives a refractive index of 1.467 at 1550 nm. After their mixing, a 2 wt.% of hydroxy methyl propiophenone (HMPP) is added in as a photoinitiator. The sols are aged for 24 hrs.

The sol for the cladding is spin-coated on silicon wafer at 1500 rpm for 30 seconds. After the spin, the film thickness can reach 9 \( \mu m \). The thickness can also be adjusted by spin speed. The film is soft baked in an oven to help the surface relax. The hard bake is performed at 140 °C for 2 hours with 1 °C/min ramp. In order to reach a lower cladding thickness of over 10 \( \mu m \) a second spin at 2500 rpm is done after the wafer is cooled down. This spin not only increases the thickness but also helps control the thickness uniformity. The wafer is again baked. The lower-cladding thickness after the second spin is over 12 \( \mu m \).

The MAPTMS-Zr for the core is spin-coated at 3000 rpm on the lower cladding in a saturated solvent vapour environment. The spin-speed and the solvent amount can be adjusted to obtain the desired thickness in the 1-5 \( \mu m \) range. The wafer is soft baked at 100 °C for 10 minutes. After the wafer cools down, the waveguides are defined by exposure through a quartz mask at 15 mW/cm\(^2\) using an I-line contact mask aligner. The sample is developed in a strong solvent such as Acetone. Afterwards, the wafer is hard-baked in the vacuum oven for 6 hours to further densify the core.

The MAPTMS-TEOS upper cladding is spin-coated at 2500 rpm on the patterned wafer. After several minutes of soft bake and 20 minutes of flood UV exposure to control the planarity of the top surface, the film is vacuum oven dried for 2 hours at 100 °C. Fig. 2 shows the cross sections of the waveguides before and after deposition of the upper cladding layer. Crack-free, high quality interfaces have been achieved for the ridge and buried waveguides.

Besides the straight channel waveguide, several integrated optical components are also fabricated in the same way.
Characterization and discussion

A tunable laser operating in the 1510 – 1580 nm range is used as the light source. The light is coupled into the waveguide with a lensed fibre. A microscope objective is used to image the near field of the output waveguides onto an IR camera. The output light is also coupled into a single mode fibre connecting to an optical spectrum analyser to measure the power and spectral response of the waveguiding devices. Fig. 3 shows the nearfield images of the modes for the ridge and buried waveguides for the structures shown in Fig. 2.

It can be seen that the ridge waveguide on the thick lower cladding can efficiently confine the mode within the core (Fig. 3a) with a small degree of asymmetry and some surface scattered light. On the other hand, the mode for the buried waveguide is very well confined and circular. This assures a low coupling loss between the waveguide and single mode optical fibers.

A y-splitter and a 4-output MMI splitter are also fabricated with the similar procedure. Figure 4 shows the top view micrograph of the buried y-splitter and its output modes. The scattered light between the modes is caused by slight scattering at the splitter region, and can be easily eliminated. Fig. 5 shows the top view micrograph of the MMI outputs and its modes. The detailed results will be reported.
Conclusion

The multi-layer waveguides by hybrid sol-gel technology are developed on high index semiconductor substrates with a simple material synthesis and fabrication method. The technology is promising for heterogeneous integration and can reduce optical loss and fabrication cost, opening the door for complex optoelectronic integrated circuits.

References: