JOURNAL OF OPTOELECTRONICS AND ADVANCED MATERIALS Vol. 13, No. 9, September 2011, p. 1130 - 1134

Laser direct writing and mask lithographic produced polymeric integrated optics

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Integrated optics is an efficient tool for fast producing waveguides. We developed two different processes adopted for providing waveguides in polymeric integrated optics: (1) a direct UV-laser writing lithographic assembly and (2) a (direct contact) mask lithographic setup. Both are photochemical processes and use different stacked polymer layers (Ormocer®), which shall be structured. We compare the properties of both assemblies and reveal several advantages and disadvantages: the direct laser ray is more variable, but less precise; the mask production is faster and more reproducible, but there are only a few opportunities to change the manufactured structures. In fact, when there is no good base in form of proper coatings, the process to create waveguides is difficult to realise, no matter which system is used.

(Received June 14, 2011; accepted September 15, 2011)

Keywords: Integrated optics, Laser direct writing, Mask lithography, Ormocer®

1. Introduction

The interest in integrated optics is continuously increasing. It is easy to produce, uses cheap materials, and enables the miniaturisation of optical components. Probably, the main advantage of integrated optics is the possibility to realise a number of optical setups in an area of a few square millimetres, like micro-ring resonators [1], fully embedded optoelectronic interconnects [2] or sensors [3,4]. Such small structures are fixed on a wafer and are insensitive to vibrations and a loss of adjustment. Due to the similarity in fabrication of semiconductor devices, the manufacturing of integrated optics is relatively easy and cost-effective.

With the development of optical polymers, like PMMA [5] or Ormocer®, a good step forward in easy processing has been achieved. Especially Ormocer® is an excellent material for shaping optical structures via ultra-violet (UV) illumination or stamping [6]. Ormocer® (organic modified ceramics) is an organic-inorganic hybrid polymer developed by Fraunhofer-Institut für Silicatforschung ISC. These polymers act as a negative photo resist, and common processing steps can be used. Herein below values are given by Micro resist, 2010. The loss of less than 0.6 dB/cm at 1550 nm is a good value for such small structures which are used in integrated optics. The surface roughness of this polymer is less than 4 nm and has a shrink while curing of 2-5%. Another important property is the glass-like refractive index of about 1.55. For coating and core structures different Ormocer® compounds with several refractive indices exist. These compounds are mixable to get the desired refractive index [7]. For a waveguide with total internal reflection, a single-mode behaviour at constant waveguide dimensions may be achieved by varying the difference of the core and cladding refractive index by mingling these compounds. Akin values of the refractive indices of core and cladding are leading to larger single-mode waveguide diameters [8]. An 8 µm core can be produced as single-mode at 1550 nm. Micro resist offers two different materials: Ormocore for the core and Ormoclad for the cladding.

We have used these Ormocer®s for producing several waveguides. In our laboratory, we focus on manufacturing step-index-waveguide-like structures. To this end, we developed two different processes to provide several waveguides in polymeric integrated optics: (1) a UV-laser direct writing assembly (LDW) and (2) a (direct contact) mask lithographic setup (ML). Both are photochemical processes and use different stacked polymer layers, which shall be structured. We aim at waveguide manufacturing for providing new sensor structures [9] and microoptical devices.

2. General aspects

The way of coating the polymers onto substrates in both processes is basically the same. A clean process environment is a necessity. We produce our waveguides in a laminar flow box of Spetec GmbH, which realises a cleanroom class of 100. Herein, our two lithographic assemblies are located. All steps are carried out in this flow box. We do not control the environmental temperature or humidity.

First, the carrier substrates have to be cleaned and their surfaces have to be optimised. We use several float glass substrates as carrier plates. The substrates are cleaned with a H_2SO_4-H_2O_2-dissolution. This dissolves all organic soiling and etches the glass surface for a better sticking of the cladding coating, in our case an unmixed Ormoclad. Before the material can be spin coated, the H_2SO_4-H_2O_2-dissolution is flushed with H_2O and thereafter with 100% isopropyl alcohol (IPA). The rest of IPA is dried by blowing with filtered air. By this way, the best adhesive contact with the cladding polymer and the used float glass substrate is produced.

Secondly, the Ormoclad cladding is generated with a spin coater. By varying the rotation speed of the coater, we can determine the height of the cladding. Film thicknesses up to 80 µm are producible without problems like a wave forming surface. After exposing the Ormoclad with UV-floodlight by an UV-LED-array, which has an optical power of 600 mW and a centre wavelength of 365 nm, the layer is developed in Ormodev. A general overview of the processing steps and detailed information about material conversion at curing is given by Buestrich et al. [10]. In order to clean the substrate and prepare for the core processing steps, we also use a flush with IPA. A mixture of 2 : 3 to 1 : 2 of Ormocore to Ormoclad reduced a dewetting effect of the core and cladding layer, see figure 1. For producing waveguides, we take a mixture of Ormocore : Ormoclad of 1 : 1. This educt is spin coated like the cladding. For structuring the waveguides, we use either the LDW or the ML. Both systems will be explained below. The fixing step is the same as the cladding step: developing with Ormodev, careful flushing with IPA and blowing with air. A post-bake for about an hour at 150 °C fixes the waveguides so that they cannot be removed. As final, a second cladding layer can be produced to cover the cores.

Fig. 1. Holes in the cladding surface because of a high viscosity of the Ormoclad and a not well cleaned wafer.

3. Fabrication of waveguides

3.1 Laser direct writing setup

When the base coating is finished and the core layer is spin coated, we can begin the waveguide structuring via the LDW. The setup is shown in figure 2. The LDW setup is characterized by a focused single-mode diode laser (A) with a wavelength of 365 nm and an intensity of 10 mW. The intensity can be varied by a filter wheel near the laser. Traced by several mirrors, the UV-beam is mode filtered (B) with an aperture and then reflected to a focussing telescope (D). A beam splitter with two beam-guiding mirrors (C) is optional. The focussing telescope forms a spot of 0.5 µm at the substrate which is fixed on an x-y-z-stage (E) of Thorlabs (NRT150 and MTS50), which can follow any CAD-designed curve.

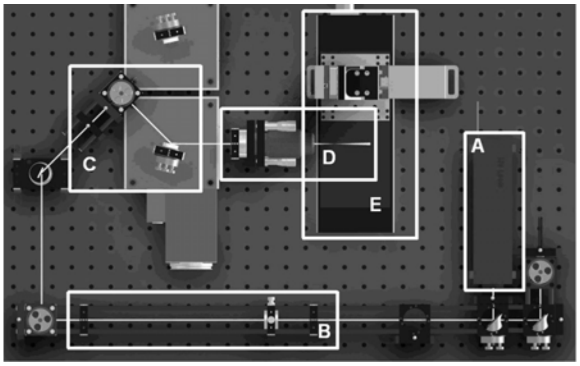

Fig. 2. Laser direct writing setup. (A) UV-diode-laser, (B) mode filter, (C) beam splitter with ray guiding mirrors, (D) beam focussing telescope, (E) x-y-z-stage.

We derived a nonlinearity of the stage and fixed it with a calibrating function for the online control. Thus, a reposition accuracy of 1 µm and 3 µm (x- and y-direction) of the beam guide is achieved and a scanning speed up to 4 mm/s is chosen. Eldada et al. [11] use the same speed to produce several coupling devices in integrated optics. Other groups report higher speeds up to 100 mm/s [12]. With a back reflection detecting photodiode we have derived a system adopted for setting the focus spot at the appropriate height above the substrate layer.

Adjusting the spot, it is possible to minimise a broadening of the produced waveguides. An overexposure of the core polymer increases the width of the waveguide because the laser beam is reflected at the back side of the glass substrate. We prevent this effect by tuning the laser intensity with a filter wheel.

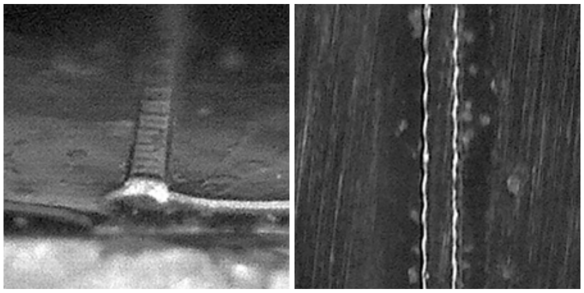

Fig. 3. LDW produced waveguides with a width of approx. 80 µm. A waveform is detectable on the top (left) and also on the sidewalls (right of the waveguide).

Based on an accuracy of 3 µm, only linear forms can be written with an acceptable precision. Round forms will result in rippled sidewalls and a high loss. Figure 3 shows LDW produced waveguides. Because of the given accuracy, the laser exposes the core layer in small steps and a waveform is detectable at the top and the sidewalls of the waveguide.

3.2 Mask lithographic setup

Another way for structuring waveguides into a core layer is to use floodlight and shadow with a lithographic chrome mask (Figure 4). We developed an easy-to-use exposure construction (Figure 5) at which an UV-LED-array of 365 nm and 600 mW radiates the core layer through a mask. The setup can also be used for lightening the cladding layer just by removing the mask.

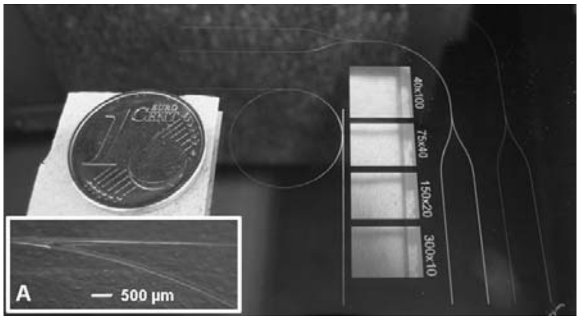

Fig. 4. Lithographic chrome mask with several couplers and gratings. (A) A produced 80 µm multimode-coupler.

The ML-setup is protected against environmental light, so that an accidentally exposure is prevented. The mask (A) lies on top of height adjusted rubber buffer. The UV-LED-array (B) illuminates the coated wafer (C) through the mask. The wafer is positioned on a slide, which can be pulled out, without opening the whole setup. The support for the wafer is reflection-minimised in order to reduce back reflections. With this solid setup it is possible to produce stacked structures.

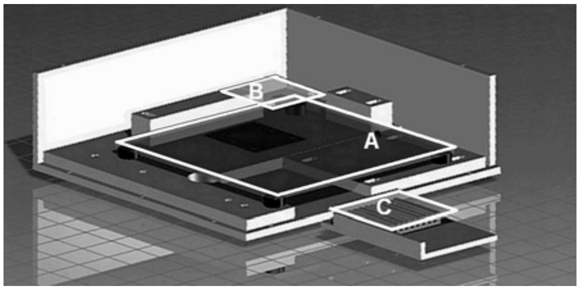

Fig. 5. Lithographic chrome mask setup. (A) chrome mask, (B) UV-LED, (C) wafer with spin coated polymer.

In case of using the assembly as a direct contact lithographic station it has to be considered, that Ormocer®s cure at exposure. Thus, a separation of the wafer and the mask is sometimes difficult. The dimensions of all the structures depend on the exposure dose, the illuminating time, the mask gaps and the mask distance. We are able to change any value except the mask itself.

The mask includes several designs and delivers high reproducible waveguides. As the structures on the mask are not variable we designed more than 20 different single and multimode structures, like ring resonators, 2x2 couplers, 1x4 couplers, test gratings or just common waveguides. These test gratings offer the possibility to define some properties of the coatings. We found the resolution of the used Ormocer®s to be related with layer height. The height of the layer determines the minimal structure dimension in x-y-direction.

4. Waveguides and layer homogeneity

In order to confirm the height of our coated layers and to make an assertion of their homogeneity, we measured the topology of coatings and the waveguides. For the first test, a wafer of 50 mm x 50 mm is partitioned in a 9-element matrix, shown in figure 6. The fringe area (2 mm) of the wafer was not exposed, because of a mound formation at the spin coating, which was observed before. So we get a smoother surface at all. By measuring the cured cladding coating mechanically, a variation of 52 µm to 65 µm is observed. The area in the middle of the wafer tends to be higher. This is due to a too short spinning time. The polymer is placed in the middle of the wafer before spin coating with a speed of 1300 rpm. Another distribution is seen at the core layer. This layer is spin coated on top of the cladding in different aimed heights.

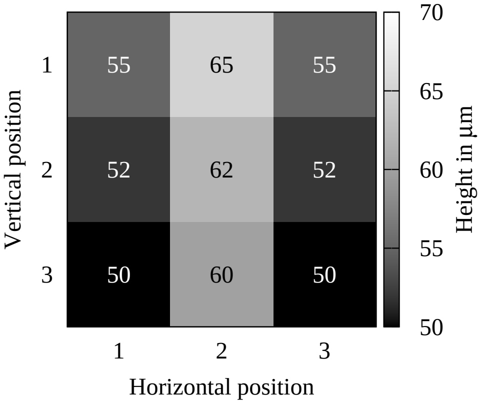

Fig. 6. Topology of a produced Ormoclad cladding, partitioned in 9 sections. The aim was a 50 µm layer.

Fig. 7 shows six different wafers with an Ormoclad layer and an Ormocore layer on top. The Ormocore layers are structured by the ML-system and the heights of these waveguides are measured. We defined three areas on the wafer in its centre, like the horizontal position 2, according to figure 6. It is observed that area A is higher than area C or E. We assume a sloping irradiance of the UV-LED. A non-uniform exposure causes a non uniform conversion of the molecules in the Ormocer®. The structures, which are not completely developed, are flushed in a later processing step.

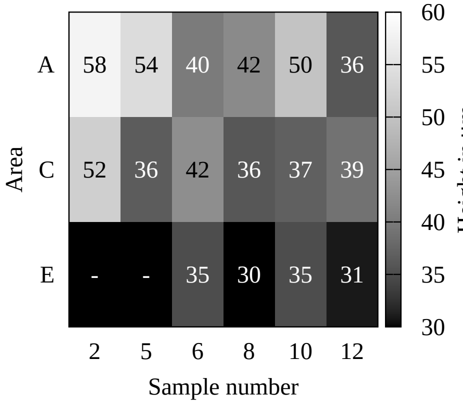

Fig. 7. Three position-topology of six different produced Ormoclad-claddings. The aim was a 50 µm layer.

A similar topology is shown in figure 8. Here, a waveguide height of 80 µm is manufactured. Five wafers are produced in the same way as shown in figure 7. The difference between both procedures is in a mingling of the reducer Ormothin into the core mixture to get the 50 µm layer. The 80 µm layer has the same mixture for the layer without the reducer. By comparing both layers, we conclude the reducer only changes the viscosity of the core mixture. A fact that is relevant in waveguide manufacturing.

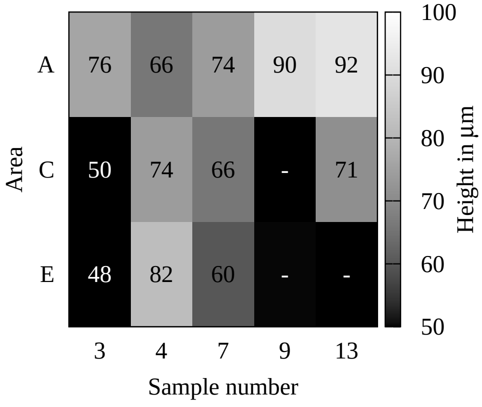

Fig. 8. Three position-topology of five different produced Ormoclad-claddings. The aim was an 80 µm layer.

Comparing the measured height with the desired height and deriving the difference and the standard deviation for each area, it is observed that area A has the closest values to the desired thicknesses. Figure 9 illustrates these proportions. The Ormothin mixed polymers show the lowest standard deviation. A low standard deviation is required for a suitable waveguide production. Another problem of an Ormothin mingling is an inferior adhesion of the core layer to the cladding layer.

These results are relevant both for the LDW and the ML. They are primarily related to the layer properties.

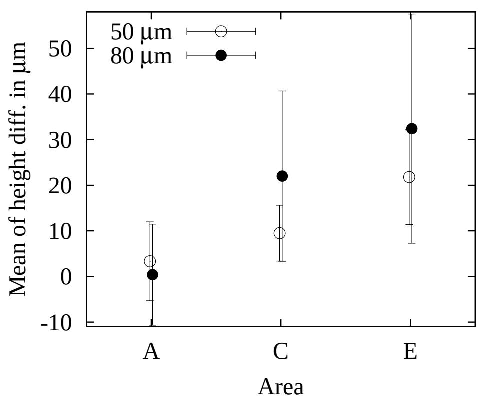

Fig. 9. Mean values of the topology of the produced Ormoclad-claddings. The error bars correspond to one standard deviation in up- and one in down-direction.

The ML-setup produces a strictly delimited smooth waveguide sidewall, see figures 10 and 11, whereas the LDW-setup produces a rippled waveguide sidewall. This is obvious by regarding figure 3. Figure 10 shows two 80 µm broad waveguides produced using the ML-setup. By defining the core layer thickness, we obtain the waveguide height after developing and curing.

Waveguides produced with the ML-setup show better optical properties than those made by LDW. Additionally, the production of waveguides with our ML-method is faster than our LDW.

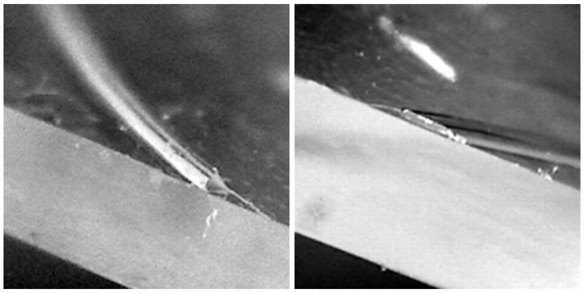

Fig. 10. ML produced waveguides. (Left) a waveguide of 80 µm width and height, (right) a waveguide of 80 µm width and 20 µm height.

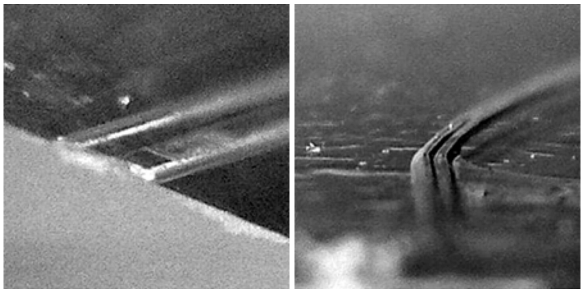

Fig. 11. ML produced waveguide with a double arch surface.

5. Conclusions

We developed two different setups for producing waveguides:, a laser direct writing and a mask lithographic assembly. We are able to structure different polymers like Ormocer®. Waveguides produced with the LDW show a periodical structure on their surfaces caused by the moving accuracy of the x-y-z-stage. The ML provides a smoother sidewall of the waveguides. The further development will concentrate in a better adhesion of the cladding and core layer to decrease the layer thickness. Then, single-mode waveguides are simpler to manufacture and we can bring our focus on micro sensing systems.

Acknowledgements

The used chrome mask was produced by University of Applied Sciences, Munich, Microsystem Technology Laboratory, Prof. Dr. H. Herberg and Dipl.-Ing. M. Kaiser, M.Sc. This work was also supported by TUM Graduate School.

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