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Polymer Light Waveguides for Nanophotonics

Manufacturing Process and Refractive Index Profile Analysis

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***Abstract*— We report a novel manufacturing method to imprint buried SM waveguides by UV lithography in polymer. The method is suitable for different multilayer structuring for all optical or opto – fluid layers. The optical layer bases on a doped polymer and is specified by high temperature stability, chemical resistance and low fluid absorption properties.**

Single mode waveguides, Integrated Optics, Nanophotonics, Polytronics

I. INTRODUCTION

Imprinting waveguides in PMMA using a DUV photolithographic mask process [1] results in asymmetrical single modes (SM) and some defects in the far field are on a high order of mismatch compared to standard SM fibers. Therefore, higher insertion loss and also modal birefringence caused by strain and stress can be found [2]. In addition, standard multimode (MM) waveguides can not be realized in PMMA by the lithography technique due to a penetration limit for the DUV light.

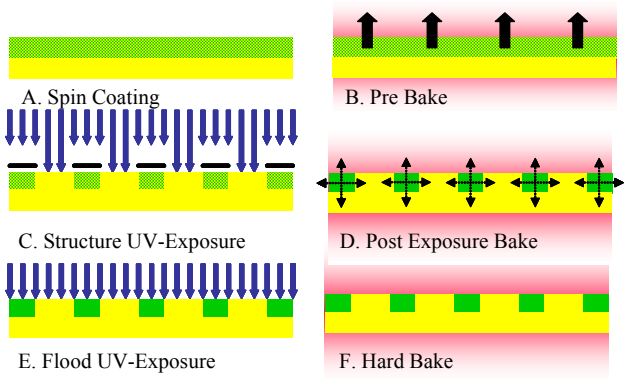

Figure 1. Schematical drawing of the main manufacturing steps.

Other different optical polymers for MM application structured as 3D rib or groove waveguides must be over covered or filled with a second polymer to build buried waveguides and can not really be used for SM waveguide production because the structure molding and/or embossing quality is limited for the small core geometry and the side wall roughness. Consequently we have been discussing to solve these problems by taking a novel chemical approach for a two component polymer based on SU 8 (Epon® oligomer). Different approaches are tested to decide on the two materials with different refractive index and the possibility for its easy adjustment by the process parameters.

II. MANUFACTURING PROCESS

The manufacturing process can be described on six main steps: A. Spin Coating, B. Pre Bake (PB), C. Structure UV-Exposure, D. Poste Exposure Bake (PEB), E. Flood UV-Exposure, F. Hard Bake (HB).

A. The epoxy based doped material (NAM) is applied to a 4 inch silicon wafer by a conventinal spin coating process. We build first a passive layer - the under cladding- which is understood as the substrate under the wave guide (WG) cores. It has a thickness of app. 20 µm. The second process step builds on the optical NAM- layer and the spin coating parameters in speed and time are optimized to get the necessary and adjusted core thickness. After finishing the following process steps, for a first order application as a mono layer WG a passivation layer – the over cladding – covers the WG cores and protects them from most influences of the environment. Especially we like to use the same NAM mixed polymer for all cover layers to realize a whole homogeneous cladding to get buried WG cores. The process technique can be seen as a unique feature for this type of WG fabrication.

B. The PB process step is variable in temperature over time. This is one parameter for refractive index tuning which is easy to handle within a range below 100 °C. The tuning works as an out diffusion process for the dopant monomer over the whole layer thickness evaporating through the surface into the air and resulting in a concentration C_x. This

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tuning process defines the index step betwenn the cladding around the later fabricated WG cores and should be app. Δn ~ 0.0035…0.0050 for SM applications.

C. The first UV- exposure causes a photo chemical reaction in NAM because it contains also a standard PAG (photo acid generator) mobilizing H^+- ions if UV light is absorbed in the NAM layer. The H^+- ions crack the end groups of the polymer rings of the SU 8 oligomer and start the polymer network linking.

D. The dopant monomer, still available in a concentration of C_x is build in into the polymer network while the cross-linking process is running. The more the monomer groups are covalently linked the lower the value of the refractive index of the UV irradiated part forming the cladding layer. Furthermore the concentration of moveable monomers decreases over time in this part. This generates a concentration gradient from the none-exposed part, forming later the core volume, to the direction of the cladding. As long as the process temperature in the PEB is held on a high level the dopant can diffuse out. Some diffuses out into the direction of the substrate and some leaves the core volume into the direction of air via the surface.

E. In the first UV- exposure the volume forming the core structures has not been illuminated. Therefore, in general, no H^+ ions from the PAG have been activated in the core volume and this part is not cross-linked yet. The flood exposure assures an activation of the H^+ ions and starts the network linking also in the core volume.

F. Finally to stabilize the network linking process for the first optical WG layer a last bake is necessary. The temperature is much higher than that of the PB and the PEB, aiming for very high temperature stability. The softening point is shifted to T_g ~ 230 °C which is nearly the same as for a pure SU 8 polymer.

III. Refractive Index Profile Characterisation

Full information about the refractive index distribution around the WG cores is very important before using BPM simulations [4] and designing more functional structures (e.g. coupling devices). Therefore we measured all refractive index profiles depending on the structure mask widths by the RNF (refractive near field) method. The measurement system we used was developed by RINCK Electronik, Jena (step size 0.1 µm, spot size ~0.5 µm @ 671 nm, index res. 0.0001, scan area up to 400 µm x 400 µm).

The WG cores were varied by using different nominal mask structure widths of 2.0 µm ≤ w ≤ 9.4 µm. Fig. 2a) shows exemplary a measured index distribution of one SM core WG in NAM designed for visible light application around 600 nm. The used nominal mask width is about w = 3.8 µm. Fig. 2b) gives three data read outs along the horizontal line scan across different cores with a nominal mask width of w = 3 / 6 / 9 µm. The horizontal scan across the core section has a gradual function and decreases from the core center in the direction of the substrate. Its function looks fully symmetrical. The vertical scan across the layer thickness has nearly a step function as assumed in a spin coated layer.

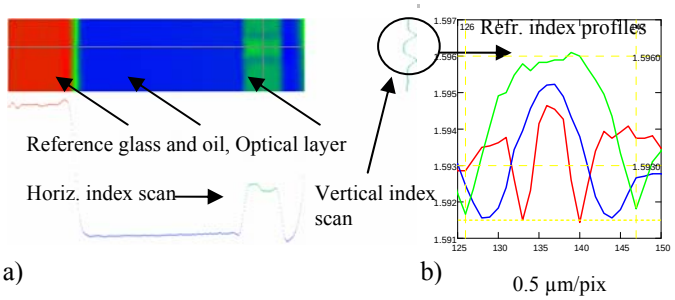

Figure 2. a) Measured refractive index scanning area on a SM WG core end face by the RNF method. b) Horizotal refr. index distribution cross over the center of SM WG cores of different mask widthes w = 3 / 6 / 9 µm

IV. Summary

We demonstrate a single material process for fabrication of embedded SM waveguides in a cladding layer with defined thickness. The used novel photo sensitive polymer mix bases on the negative resist SU 8. The mixture (C_{1-x} + C_x) of the host – guest system named NAM is variable in the concentration ratio and can be adjusted via a temperature process. Because the refractive index of the guest monomer is significantly lower than the host index of SU 8 the index of NAM can be tuned always below the refractive index of the pure SU 8. Generally a diffusion process is used for the description of an index step adjustment by UV exposure and temperature treatment. The manufacturing process technique can be used for both SM and MM waveguides. The core profiling referenced on different standard fibers for the visible and the near infrared range of wavelengths depends on the requested application in the fields of data communications. The lithographic imprinting into the used NAM polymer shows significant better mode guiding behaviors which have nearly exact Gauss symmetry. Furthermore, mode distribution analysis comes up with excellent mode field diameters (MFD) [3]. The numerical aperture (NA) referenced on standard SM fibers was measured by FFP analysis and matches well. An extensive RNF analysis shows nearly a step index profile in the vertical direction of the layer thickness and a fully symmetrical gradually growing core index from out side the substrate in the direction of the core center.

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