Polymer microlenses for collimating light from single-mode silicon oxynitride optical waveguides

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Abstract—**We propose a novel technique for microlens fabrication which is compatible with silicon oxynitride technology, and enables the collimation of light exiting the waveguides into beams with divergence angles of ~0.52°.**

Keywords-arrayed microlenses; integrated optics; waveguides

I. Introduction

Numerous studies have addressed microlens fabrication for different material platforms, and using different techniques [1-6]. Most of these studies aim at using the microlenses in array configurations in which the incident light is directed orthogonally to the plane of the microlenses. Example applications are, but not limited to, free-space optical interconnection networks [1], concentrator photovoltaic systems [2], adaptive optics wave-front detection [3]. On the other hand, microlenses intended for waveguide platforms have been limited to in-plane focusing of light in one lateral direction [4-6], while requiring light to be guided in the vertical direction. Therefore, these lenses present low efficiencies when used to direct light on samples that are placed at large distances from the chip. This functionality is needed, for example, in medical applications that involve Raman spectroscopy or optical coherence tomography (OCT), where large efforts are being made towards the realization of low-cost integrated devices [7, 8]. In this work we propose a novel fabrication technique for the realization of microlenses that enable out-of-chip collimation (as well as focusing) of light from silicon oxynitride (SiON) waveguides. The lenses are realized by low temperature reflow of positive photoresist, and the fabrication steps, presented in the next Section, are compatible with SiON technology. In the last Section we present our simulation results which show that very small beam diameters are achievable with low divergence angles.

II. Design and Process Flow

The lenses are designed to collimate light from SiON waveguide structures embedded in a boron-phosphorus doped silica glass (BPSG) cladding. The choice for SiON as the waveguide core is motivated by the large flexibility given by this material in the design phase in terms of tunability of the refractive index, which can be varied continuously from 1.46 to 2.0 by changing the ratio between the oxygen and nitrogen content in the material [9]. The choice of BPSG as a cladding material is mainly motivated by the possibility of depositing thick layers (> 10 μm) with reasonably short deposition times [10]. Thick layers are, in fact, necessary to host the microlenses as explained later in this Section.

In Fig. 1, we show a schematic of a microlens with radius *R*, positioned at a distance *d* from the waveguide facet. The lens is asymmetric, as it is embedded between two different media (BPSG and air). The purpose of having BPSG between the waveguide and the lens, instead of air, is twofold. Firstly, it reduces back reflections from the waveguide end-facet. Secondly, it reduces the angular aperture of the waveguide, which enables positioning the lens at its focal distance without excessive losses due to overfilling the lens aperture. In the design phase the refractive index of SiON, as well as the waveguide geometry and lens radius can be fine tuned to reduce these losses to a minimum (compatibly with the waveguide properties required for the application). In the current design there is a vertical displacement of the lens with respect to the waveguide which is equal to the thickness *a* of the upper cladding. The displacement causes a vertical tilt of the beam of a few degrees as will be discussed in the next Section. The thickness *a* must be chosen in a way to avoid light exiting the waveguide to reach the upper BPSG-to-air interface, since this would cause unwanted reflections leading to a distorted output beam.

The lens, made from photoresist, is located in front of the waveguide, partially embedded in the BPSG layer. For this to be possible a semi-spherical hole is first etched into the BPSG by isotropic etching using buffered hydrofluoric acid (BHF) in which the etch rate is ~450 nm/min [10]. The hole is then filled with the lens polymer (photoresist AZ 9260). As shown in Fig. 2, the fabrication steps involve the use of two masks: a first mask is used for defining a hole of around 2 μm in diameter from which the isotropic etch is initiated; a second low resolution mask is used for defining the lens.

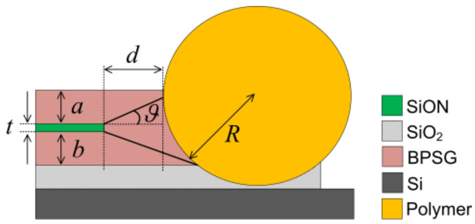

Figure 1. Schematic of microlens, where *t* is the thickness of the SiON layer, *a* and *b* are the thicknesses of the upper and lower BPSG claddings, *d* is the distance of the micro-lens from the waveguide facet, *R* is the lens radius, and ϑ is the angular apertue of the waveguide inside the BPSG.

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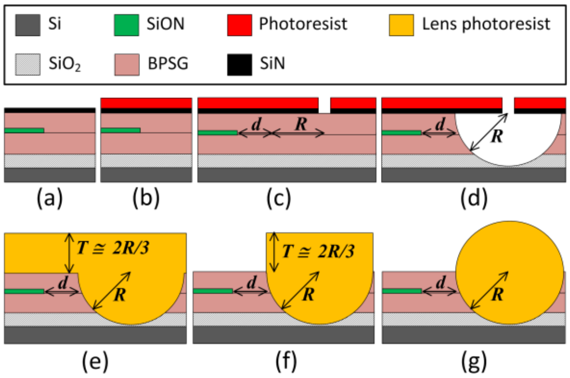

Figure 2. Process flow of microlens fabrication on pre-existing waveguide structure. (a) SiN deposition, (b) Spinning of photoresist and mask exposure, (c) development of photoresist and etching of SiN, (d) Isotropic etch of BPSG through buffered hydrofluoric acid (BHF) to achieve a semi-sphere with radius *R*, (e) Spinning of lens photoresist with height $T \cong 2R/3$, (f) Exposure and development of resist using the lens mask, (g) reflow of resist at ~130 °C.

For the isotropic etch (see Fig. 2(a-d)) we use SiN as a masking material due to its low etching rate (< 1.3 nm/min) in BHF [11]. In order to obtain a spherical lens we spin photoresist (AZ 9260) with thickness *T* approximately equal to $2R/3$ (see Fig. 2(e)). The thickness of the photoresist layer must be chosen in a way that after lithography and resist reflow (see Fig. 2 (f-g)), the volume of the photoresist above the surface of the chip is equal to that of the photoresist embedded in the BPSG. For this reason we must take into account the loss of material due to evaporation during the pre-exposure softbake and the successive reflow phase. It is important that, since half of the sphere is hosted in the BPSG and thermal oxide layers, the total thickness of these layers is in the order of the lens radius *R*. Smaller thicknesses are acceptable in case the light does not reach the silicon substrate, i.e. the angular aperture of the waveguide is small.

III. Simulation Results

We present our simulation results on a microlens structure with the following parameters (refer to Fig. 1): a = 6 µm, b = 15 µm, R = 45 µm, d = 19 µm. The waveguide is designed to be single-mode in the wavelength range 800-900 nm, with core index of 1.552, cladding index of 1.453, and cross-section of 2 µm × 0.3 µm. We considered the thickness of the thermal oxide (on silicon) to be 8 µm. To simulate the structure we make use of the beam propagation method (BPM) [12]. In particular we use 2D BPM with Pade order 3 implemented by Phoenix BV [http://www.phoenixbv.com]. We launch light at a wavelength λ = 850 nm into the waveguide and compute the intensity profile at distances of 2.5 mm and 3 mm from the lens center. For the 2D simulation the waveguide structure is first reduced to an equivalent planar structure via the effective index method. The vertical displacement of the lens with respect to the waveguide by the distance a causes a vertical tilt of the beam of 5.7°. In Fig. 3 we show the obtained intensity profiles at 2.5 mm and 3 mm from the lens center. As can be seen from Fig. 3, the lens produces a beam with an almost circular profile, having FWHM of ~45.5 µm in the vertical direction and ~46.1 µm in the horizontal direction, with divergence angles of 0.80° and 0.52°, respectively in the two directions. The beam profile can be made perfectly circular, in principle, by tapering the waveguide in the horizontal direction. However, at this stage we did not perform this optimization. We observe that without the lens the FWHM of the beam in the horizontal direction, at 2.5 mm from the waveguide facet, is ~1350 µm (30 times larger), and the divergence angle ~15.50° (30 times larger), while in the vertical direction we have a FWHM of ~1930 µm with divergence of 22.14°.

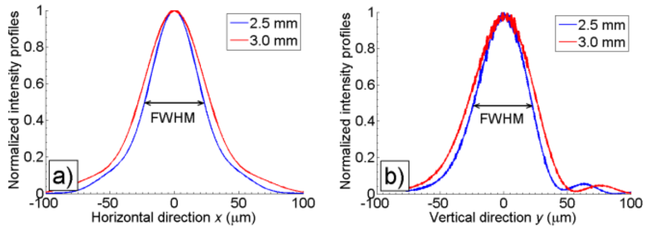

Figure 3. Beam profiles in the horizontal (a), and vertical (b) directions computed at a distances of 2.5 mm and 3.0 mm from the lens center.

IV. Conclusions

We presented a novel technique for the integration of spherical waveguide lenses in SiON technology. The proposed lenses enable collimation of light in both horizontal and vertical directions with small divergence angles. Our method opens new possibilities for the realization of low-cost on-chip devices for different applications such as spectroscopy and OCT. The fabrication of the devices is currently under way.

V. References

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