Maxwell Fisheye for Use as an Optical Cross-Connect

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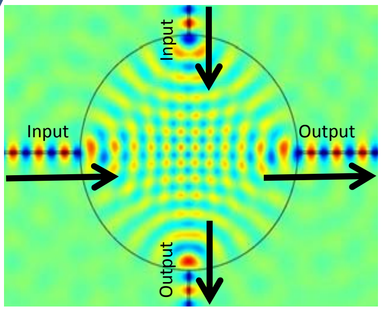
Introduction

The Maxwell fisheye lens is a non-homogenous, aberration free, perfectly focusing lens. This lens focuses light from a point source on the surface of the lens to another point on the opposite side. While the fisheye has been studied in the past for its application in imaging, here we extend its use for chip based photonics. Specifically, we are developing the lens for use as a massively parallel and low-loss optical cross-connect. Our study focuses on creating this lens in a silicon-on-insulator (SOI) platform which is commonly used in optical circuitry because of its high refractive index contrast. An important part of this project was developing a precise reactive ion etch (RIE) transfer process with low roughness and accurate pattern transfer from a lithographically defined pattern. This was done by varying the chemistry, power, and pressure of the etch. Specific trends in the silicon transfer were noted and then applied to the fabrication process in order to construct a smooth lens.

Motivation

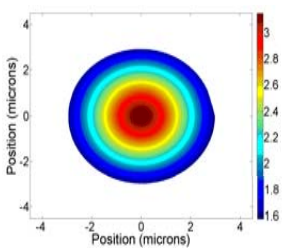


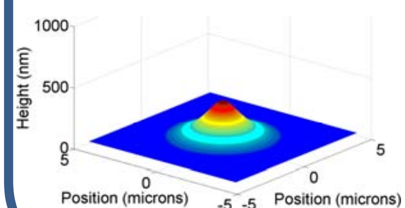
Waveguide Coupled Maxwell Fisheye. Two input waveguides are simultaneously coupled to a 3 µm radius fisheye lens. Each waveguide exhibits an extremely low loss of -0.1 dB, mostly due to reflections at the boundary. Up to 8 waveguides can be simultaneously coupled to the lens with little to no reduction in the transmission.

Gradient refractive index of the Maxwell Fisheye Lens. The Maxwell Fisheye has a radially varying refractive index given by:

$$n = \frac{n_o}{1 + \left(\frac{r}{R}\right)^2}$$

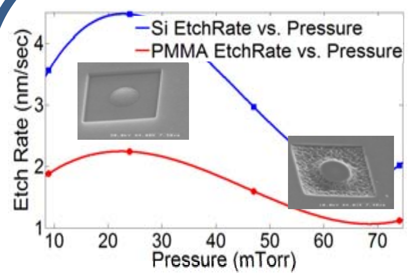
where r is the radial position, R is the outer radius, and n_o is an arbitrary scaling factor.



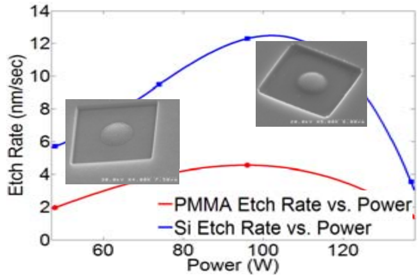


3D Height Profile of the Fisheye Implemented in Silicon. Through waveguide theory a correlation can be found between modal refractive index and the height of a silicon structure. The lens is created by grayscale patterning of PMMA and reactive ion etching (RIE).

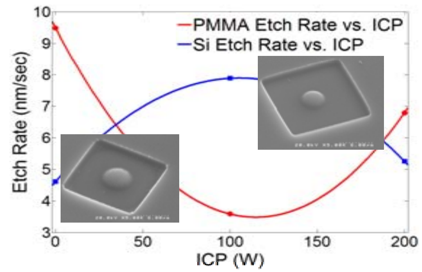
Etch Rate Trends



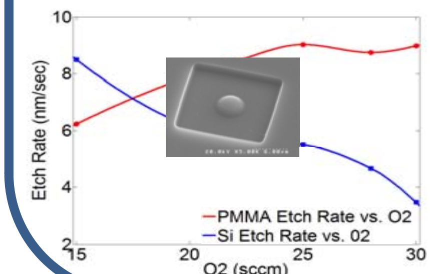
Etch Rate vs. Pressure. In order to construct a smooth lens, trends in the etch rate and roughness of Si / PMMA were found. By lowering the pressure in the RIE chamber a higher etch rate of 4.5 nm/sec was achieved and the roughness of the structure was dramatically reduced. This produced an RMS roughness of 33 nm.



Etch Rate vs. RIE Power. Using low pressure, an increase in power resulted in a reduced roughness from 33 nm to 6 nm. *It was found that Kapton tape (used as a secondary etch mask) significantly influenced etch rate.* Removal of the tape resulted in the Si and PMMA etch rates inverting (see below).

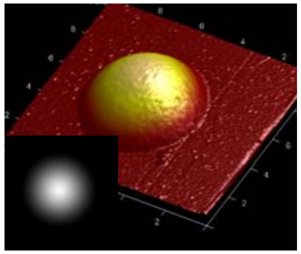


Etch Rate vs. ICP Power. In addition to the low pressure and RIE power, an inductively coupled plasma (ICP) was incorporated into the etch settings. At 200 W ICP the roughness was reduced from 6 nm to a range from 4-5 nm. The addition of ICP created a build up of heat on the sample, so a 4 inch silicon wafer was placed bellow the sample to negate this effect.

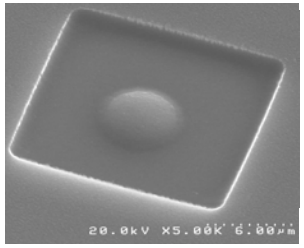


Etch Rate vs. O_2 Content. By changing the O_2 level during etching, a common etch rate between the PMMA mask and the Si was found, allowing for an accurate transfer without distortion of the original grayscale pattern.

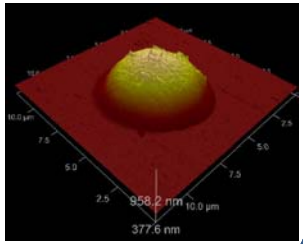
Final Results



AFM of Grayscale PMMA Pattern. After writing and developing the grayscale pattern, a reflow procedure was added to further reduce the roughness. The sample is baked at 125°C for 60 seconds before it is placed in the RIE. The inset is the grayscale dose pattern which was written.



•SEM of Final Grayscale Pattern in Si. The current chemistry and RIE settings used to produce this structure are as follows: 25 mTorr Pressure, 100 W Power, 200 W ICP, 25 sccm SF_6, 18 sccm O_2. The current grayscale pattern is not the Fisheye but instead a similar hill shape which has been used for testing.



AFM of Final Grayscale Pattern in Si. The result of this process is an RMS of 2-3 nm for the background and a 6-14 nm roughness for the lens. The structure is transferred with minimal deformity of the written pattern, though some lateral etching is observed, resulting in a smaller Si pattern.

Conclusion

The combination of low pressure, moderate RIE power, moderate ICP power, and reflow allow for a smooth and accurate transfer of a grayscale pattern into silicon. Based on this work, the Fisheye lens as well as a number of other gradient index devices can be realized for use in on-chip photonics applications.

Acknowledgments

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