Optical Waveguides in Silicon
Andreas G. Andreou

This writeup is adapted from Fall 2002, final project report for 520.773 by Robert Winsor.

September, 2003

ABSTRACT

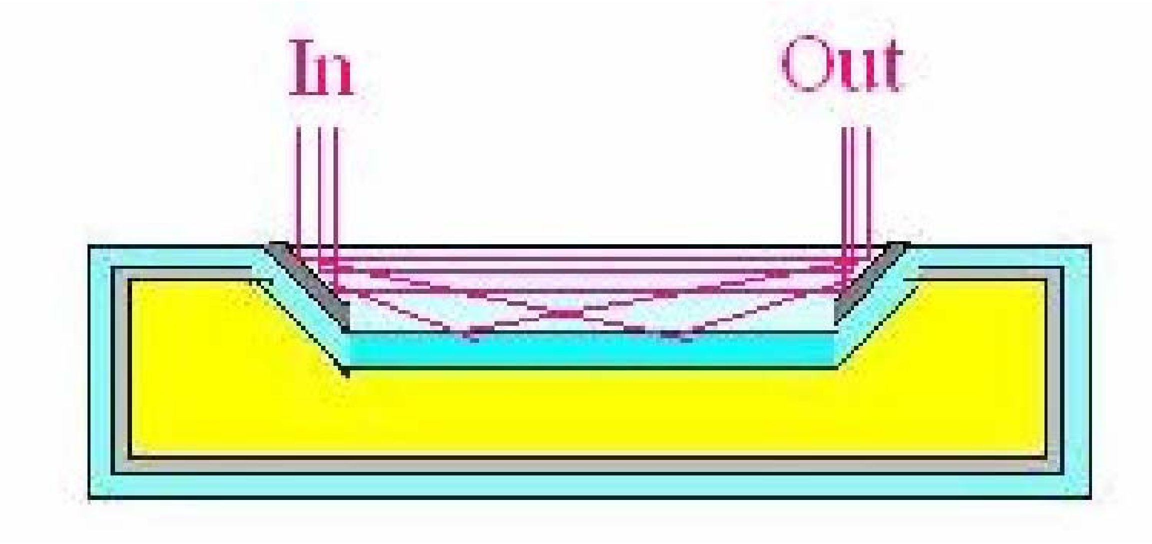
This lab course is intended to give students hands-on experience with microfabrication. The project is to make optical waveguides on a chip. From class, students will learn how to do photolithography, silicon bulk-etching, oxidation, metallization, lift-off, and glass to wafer bonding. After completing chip fabrication, the waveguides will be tested and a small system will be assembled to demonstrate Gb/s communication within a silicon integrated circuit.

INTRODUCTION

As the need for faster processing speeds in computers grows ever larger, a fundamental limit is being realized that wires used to connect circuits can not transmit information beyond a certain limiting speed. This speed limitation is based on the many factors, but can be summarized by simply stating that long paths of communication are slower than what is desired. If high data rates are to continue to grow, we must look at using other methods of transmitting data rather than relying on electrons traveling down long wires.

Optical methods of communication are already in heavy use in industry, but not at the computer-chip level. Fiber optics is a great method of transmitting high data rates over very large distances. However, their use has not been applied to microchips due to the complexity of coupling a fiber to a transmitter or receiver. Furthermore, many problems in communicating at the microchip level do not require paths that exceed many centimeters in length. Fibers require a substantial length of material to be useful by themselves, due to limitations of bending radius and the requirement for couplers to get the energy into the fiber. In many ways, fibers are not an ideal choice for optical communications within a microchip.

A waveguide in use at the microchip level needs to be easy to fabricate, easy to route, and have a built-in means of coupling light from the source into the waveguide. It is desirable for such a waveguide to be manufacturable using well-known methods of lithography and microfabrication so that their inclusion on an assembly line of an existing process is straightforward and involves minimal cost impact. It also needs to be capable of routing signals in 2-dimensions, as not all applications will have a straight-line path from the transmitter to the receiver.



To make these waveguides, an anisotropic etch is performed on a <100> silicon substrate (1). By etching channels along the <110> direction on the wafer, a waveguide of desirable geometry can be produced. The etched channel will have a triangular cross-section and the ends of the groove will have mirror-like facets with optical quality flatness. Since the substrate is silicon, it is easy to grow a thick layer of oxide, and this oxide has an index of refraction, n=1.538 at 800nm. This serves as a good cladding material. The groove is then filled with another material of higher index. For this experiment, SU-8 was chosen because it is readily available and has an index of 1.589 at 800nm (Appendix A). This index will create total internal reflection (TIR) with an acceptance angle given by the following formula:

$$\frac{n1\sin(\theta)}{n2} \geq 1 \qquad (1)$$

Using this formula and the index value for SiO_2 as n2 and the index of SU-8 as n1, the total angle of acceptance (twice the value for θ above) for this waveguide is ~28degrees. This is a value suitable for many applications.

DESIGN AND FABRICATION PROCESS

Creating the grooves in the substrates first requires growth of an oxide layer on the wafer. These waveguides were chosen to be ~200microns wide, and due to the crystallography of silicon and the anisotropy of the etch, this results in a groove depth of about 142 microns. Anisotropic etching of silicon can be accomplished in different ways (Chapter 5 in the book). In this project we use KOH.

After growing the initial oxide, positive photoresist is spun onto the wafer (both sides), and the shapes of the grooves are exposed (see Figure 1). This exposes the oxide layer so that it can be quickly etched using a buffered HF acid solution. The HF etching removes the oxide where the silicon substrate needs to be etched. After the hard mask is patterned, the photoresist is cleaned from the wafer and it is then immersed in the KOH etching solution.

After the KOH etching is complete, the wafers are cleaned and placed in an oven for wet oxidation. The wet oxidation should be as thick as possible for maximum efficiency of the waveguide. For this experiment, an oxide layer of at least 4 μm was desired, and therefore a very lengthy overnight oxidation time (approximately 30 hours).

Although silicon entry and exit mirrors are somewhat reflective, an aluminum coating was desired on these facets to improve efficiency. It is expected that aluminizing these facets should increase reflectivity to ~90%, as compared with a likely value of something near 30% without aluminizing. Reflections from a silicon substrate at these angles would also be highly polarized, requiring further complexities. A good waveguide should exhibit true total internal reflection, and aluminum would attenuate part of the signal at each reflection. In fact, even at 97% reflectivity, these waveguides would be horribly inefficient due to the many reflections that light takes as it travels through the waveguide. The wafers were thus aluminized through a shadow silicon mask to selectively deposit metal only in the entry and exit points of the waveguides.

Finally, the waveguides were filled with SU-8 to form the core.

The entire fabrication sequence is summarized below.

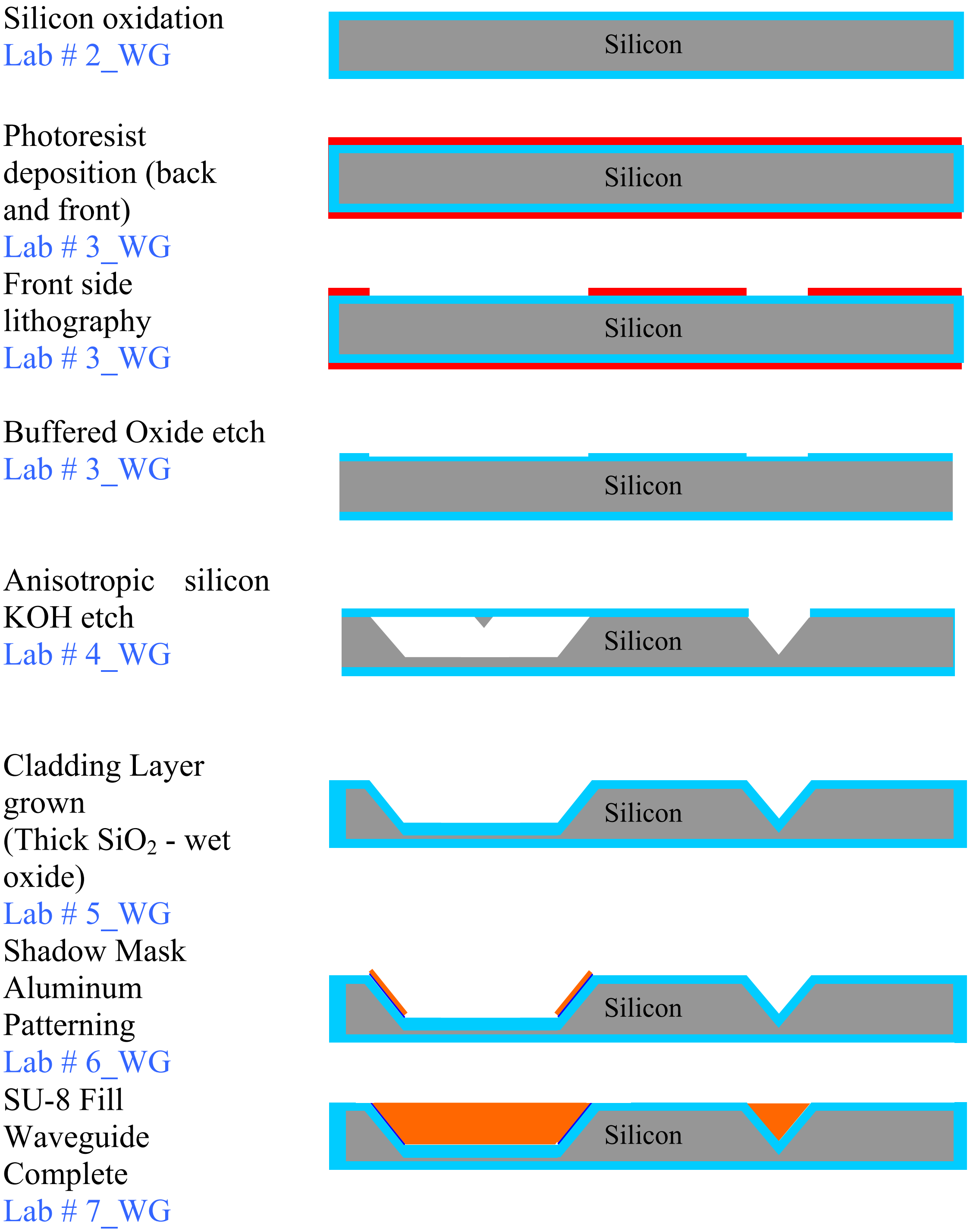


Figure 1. This series of sketches depitcts a representation of the steps to make the waveguide. Both a side view and end view are shown as if on the same wafer, depicting a cross-section through the center of a groove (left side of wafer) and a neighboring groove running perpendicular to it. The lab work timeline is also shown.

APPENDIX A: Optical Data for SU-8

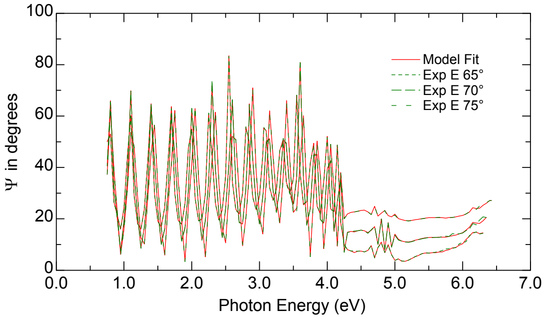
Wafer SU-8 2, Nominal 1.53 microns

Data were fit over the spectral range 0.75-6.45 eV. The film was assumed transparent below 3.5 eV (354 nm).

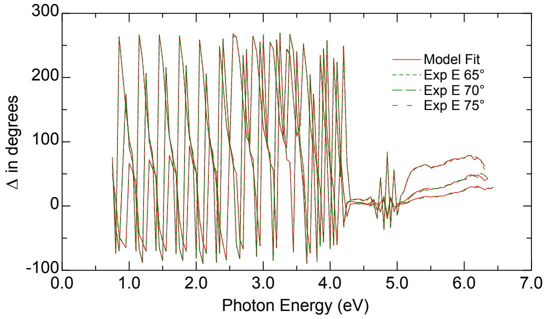
1	su-82	1546.8 nm
0	silicon	1 mm

Thickness Nonuniformity = 1.45%

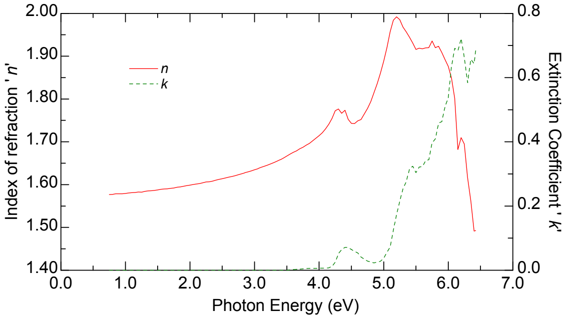
Generated and Experimental



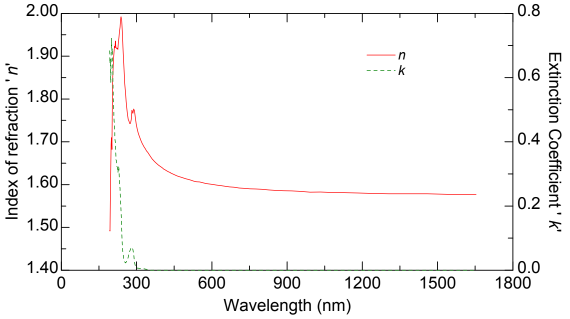
Generated and Experimental



SU-82 Optical Constants

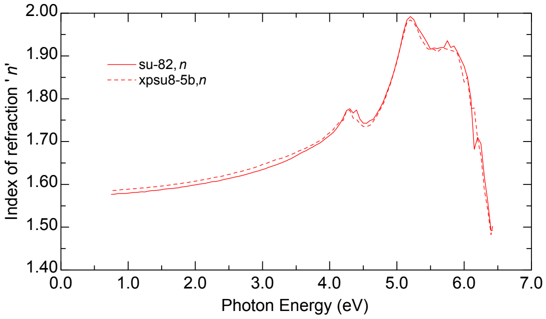


SU-82 Optical Constants

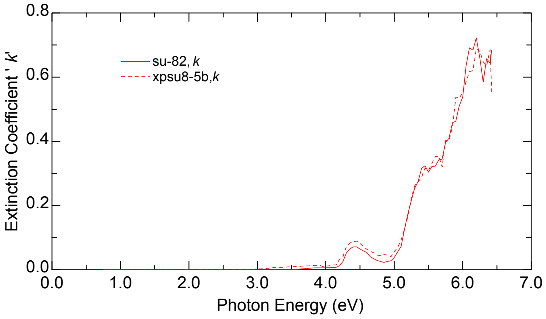


Here are the optical constants of both SU-8 films plotted together for comparison.

SU-8 Optical Constants: Comparison



SU-8 Optical Constants: Comparison



Another sample of XP SU-8 was provided (XP SU-8 10) but the nominal thickness of 50 microns was far too thick for VASE® analysis.

Wafer SU-8 2

nm	n	k
193	1.492	0.684
193.75	1.491	0.644
195.28	1.561	0.657
196.83	1.617	0.584
198.4	1.695	0.660
200	1.710	0.722
201.63	1.682	0.684
203.28	1.802	0.691
204.96	1.849	0.635
206.67	1.876	0.538
208.4	1.893	0.510
210.17	1.909	0.463
211.97	1.923	0.458
213.79	1.920	0.409
215.65	1.936	0.396
217.54	1.920	0.344
219.47	1.919	0.342
221.43	1.917	0.323
223.42	1.919	0.321
225.45	1.916	0.304
227.52	1.931	0.324
229.63	1.944	0.316
231.78	1.957	0.276
233.96	1.968	0.254
236.19	1.985	0.216
238.46	1.992	0.173
240.78	1.984	0.125
243.14	1.957	0.072
245.54	1.920	0.056
248	1.889	0.038
250.51	1.860	0.028
253.06	1.836	0.026
255.67	1.815	0.023
258.33	1.794	0.026
261.05	1.778	0.029
263.83	1.765	0.034
266.67	1.752	0.041
269.57	1.749	0.054
272.53	1.743	0.059
275.56	1.743	0.064
278.65	1.753	0.071
281.82	1.774	0.071
349.3	1.671	0.001
354.29	1.667	0
359.42	1.662	0
364.71	1.658	0
365	1.658	0
370.15	1.655	0
375.76	1.652	0
381.54	1.648	0
387.5	1.646	0
393.65	1.643	0
400	1.640	0
405	1.638	0
406.56	1.637	0
413.33	1.635	0
420.34	1.632	0
427.59	1.630	0
435.09	1.628	0
436	1.627	0
442.86	1.625	0
450.91	1.623	0
459.26	1.621	0
467.92	1.619	0
476.92	1.617	0
486.27	1.616	0
496	1.614	0
506.12	1.612	0
516.67	1.610	0
527.66	1.608	0
539.13	1.607	0
551.11	1.606	0
563.64	1.604	0
576.74	1.603	0
590.48	1.601	0
604.88	1.600	0
620	1.599	0
635.9	1.598	0
652.63	1.596	0
670.27	1.595	0
688.89	1.594	0
708.57	1.592	0
729.41	1.591	0
751.52	1.590	0
nm	n	k

285.06	1.767	0.065
288.37	1.777	0.052
291.76	1.773	0.025
295.24	1.755	0.012
298.8	1.741	0.008
302.44	1.730	0.007
306.17	1.721	0.006
310	1.714	0.006
313.92	1.708	0.006
317.95	1.702	0.006
322.08	1.696	0.006
326.32	1.692	0.005
330.67	1.687	0.004
335.14	1.684	0.003
339.73	1.679	0.003
344.44	1.675	0.002
775	1.590	0
800	1.589	0
826.67	1.588	0
855.17	1.586	0
885.71	1.586	0
918.52	1.585	0
953.85	1.584	0
992	1.582	0
1033.3	1.583	0
1078.3	1.582	0
1127.3	1.581	0
1181	1.580	0
1240	1.579	0
1305.3	1.578	0
1458.8	1.578	0
1550	1.577	0
1653.3	1.577	0