Integrated Silicon Nitride Waveguides: Optimization of Fabrication

Alex Bryant
Materials Science and Engineering, University of California, Berkeley

NNIN REU Site: Cornell NanoScale Science and Technology Facility, Cornell University, Ithaca, NY
NNIN REU Principal Investigator: Professor Michal Lipson, Electrical and Computer Engineering, Cornell University
NNIN REU Mentors: Daniel Lee and Jaime Cardenas, Department of Electrical and Computer Engineering, Cornell University
Contact: awb88@cornell.edu, ML292@cornell.edu, YL482@cornell.edu, jc922@cornell.edu

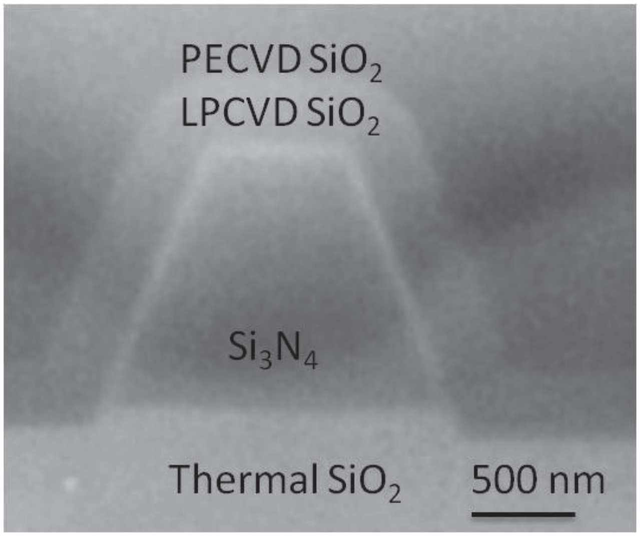

Figure 1: Scanning electron microscope (SEM) image showing the trapezoidal shape of previous waveguides that have been produced from Si_3N_4 [1].

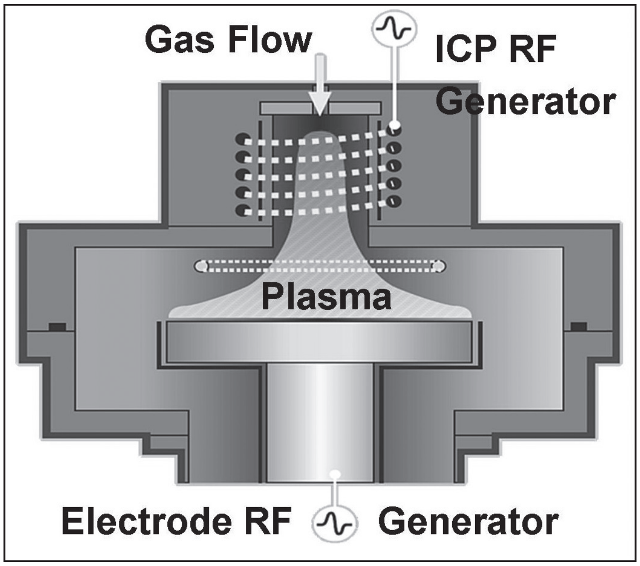

Figure 2: Typical ICP configuration showing antenna coil for plasma generation and electrode for ion acceleration [3].

Abstract and Introduction:

Integrated waveguides enable the use of photons for transfer of data in a manner similar to that of electrons in integrated circuits. Silicon nitride (Si_3N_4) is an ideal material for these devices as it is transparent in the wavelengths between 300 nm and 5 μm, has a high refractive index, and does not have non-linear power losses. However, as seen in Figure 1, previous etch processes with silicon oxide (SiO_2) masks have produced sub-optimal waveguides [1]. An etch process with high selectivity and 90° sidewalls will enable enhanced optical performance and lower propagation loss. This will allow fabrication of high performance integrated photonic devices.

This project utilized the existing SiO_2 mask Si_3N_4 plasma etch process with trifluoromethane (CHF_3) and O_2. It was seen in the Blain, et al., paper [2] that the addition of nitrogen increased the Si_3N_4 selectivity, so N_2 was added into the etch chemistry. Varying the parameters of CHF_3, O_2, and N_2 flow rates, bias voltage, and pressure in multiple design of experiments (DOEs) and then measuring the resultant etch rates, selectivities, and sidewall angles allowed for the creation of an etching process optimized for the Oxford 100. The results enable the fabrication of 90° sidewalls with a selectivity of roughly 1.8:1.

Experimental Procedure:

For the plasma etching, we chose to use the Oxford 100 with the configuration shown in Figure 2 because, as an inductively coupled plasma (ICP) system, the plasma density and ion energies are decoupled. This allowed for high aspect ratios and small feature etching [3].

Then, as it was seen in the literature that a high selectivity of 100:1 was achieved for the chemistry $NF_3/O_2/NH_3$ in an isotropic downstream process with high pressure, RF power, and flow rates as well as very low temperature [4], nitrogen was added into the usual etch chemistries CHF_3/O_2 and CF_4/O_2 of our Oxford 100. This addition was meant to

$$
\begin{aligned}
2NO + 2N_{(S)} &\rightarrow 2N_2 \uparrow + O_2 \uparrow \\
NO + N_{(S)} &\rightarrow N_2O \uparrow \\
NO + N_{(S)} &\rightarrow N_2 \uparrow + O_{(S)}
\end{aligned}
$$

Figure 3: Mechanisms by which nitrogen in the surface is removed due to the addition of nitrogen into the plasma chemistry [2].

result in the same constituent elements being present as was in the 100:1 selectivity etch chemistry, with the addition of carbon. The Blain, et al., paper [2] further verified this as a reasonable method of increasing the selectivity, showing that an addition of nitrogen increases the etch rate of Si_3N_4 relative to SiO_2 due to the formation of NO gas in the plasma, which subsequently reacts with the surface in one or more of the mechanisms shown in Figure 3.

As such, multiple 2-level Fractional Factorial DOEs were run with both of these chemistries, where the factors concerned were: CF_4 or CHF_3 flow rate, O_2 flow rate, N_2 flow rate, pressure, RIE power, and ICP power. From these DOEs, general trends were determined for each of these factors as well as their interactions. This enabled further DOEs which focused further on the parameter spaces which resulted in the most favorable results.

During each DOE, the fabrication process involved the following steps: First, with low pressure chemical vapor deposition, about 50 nm of high temperature silicon oxide (HTO), and then 350 nm of Si_3N_4, and then another 250 nm of HTO were deposited. Then, about 750 nm of SPR 955-CM photoresist was spun on top. This resist was then patterned into the shape of the waveguides with the Autostepper. The top SiO_2 layer was then etched in the Oxford 100, and the resist was stripped in an oxygen plasma in a coupled reactive ion etcher. Finally, the Si_3N_4 was etched with the SiO_2 layer as a mask, leaving the SiO_2 mask as cladding.

Results and Conclusion:

The etch rate and selectivity were determined using a FilMetrics (an interferometer) and the changes in thickness of the SiO_2 mask and Si_3N_4 layers after the Si_3N_4 etch. To determine the sidewall angles, the wafers were cleaved perpendicular to the waveguides, and the resulting pieces were mounted in the SEM on a 90° mount after Au/Pd were sputtered on top to reduce charging of the dielectric material.

Six DOEs were performed with the intention of finding the highest selectivities possible. Then, SEM imaging was performed to determine if the highest selective parameters also resulted in 90° sidewalls. The CF_4 chemistry produced the highest selectivities, but their sidewalls were not perfectly 90°. However, the CHF_3 chemistry resulted in a slightly lower selectivity of about 1.8 and had perfect 90° sidewalls. Further, the waveguides which were coupled (less than a micron apart) were also resolved to a high degree of precision. The CHF_3 etch devised here will now be used by the Lipson group for the fabrication of their Si_3N_4 waveguides.

Acknowledgements:

I would like to thank my principal investigator, Professor Michal Lipson. I also wish to acknowledge the guidance and assistance of my mentors Daniel Lee and Jaime Cardenas. Further, I appreciate the help of Meredith Metzler, Vince Genova, and the CNF staff. In addition, this project could not have happened without funding from the National Science Foundation and the National Nanotechnology Infrastructure Network Research Experience for Undergraduates (NNIN REU) Program, the Cornell NanoScale Science and Technology Facility, and Rob Ilic and Melanie-Claire Mallison, the CNF REU Program Coordinators.

References:

[1] Levy, J. et al.; "CMOS-compatible multiple-wavelength oscillator for on-chip interconnects"; Nature Photonics, Vol 4, January 2010.

[2] Blain, M. G. et al.; "Role of nitrogen in the downstream etching of silicon nitride"; J. Vac. Sci. Technol. A, Vol. 14, No. 4, Jul/Aug 1996.

[3] Oxford Instruments; "ICP Chamber Diagram"; <http://www.oxford-instruments.com/products/etching-deposition-growth/processes-techniques/plasma-etch/icp/Pages/icp.aspx>.

[4] Wang, Y. et al.; "Ultrahigh-selectivity silicon nitride etch process using an inductively coupled plasma source"; J. Vac. Sci. Technol. A, Vol. 16, No. 3, May/Jun 1998.

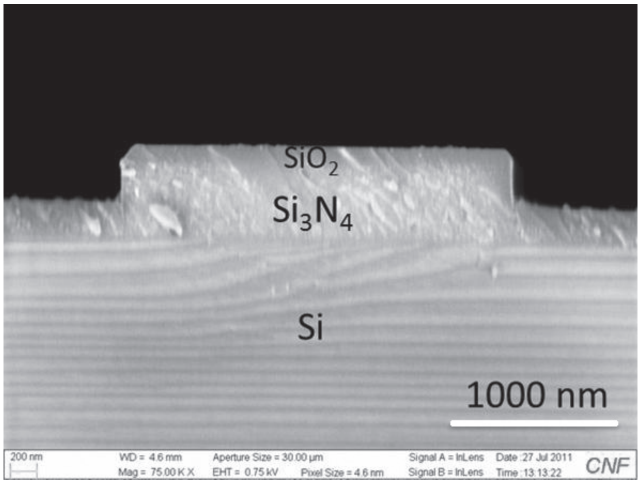

Figure 4: SEM image showing 90° straight sidewalls from developed etch process.