Versatile Silicon-Oxynitride Planar Lightwave Circuits for Interconnect Applications

G. L. Bona, R. Germann, F. Horst, B. J. Offrein and H. W. M. Salemink
IBM Research, Zurich Research Laboratory
CH-8803 Rüschlikon, Switzerland
glb@zurich.ibm.com

Abstract

Low-cost silica (SiO_2) on silicon integrated planar lightwave components for applications in interconnect and optical networks have been developed. Using silicon-oxynitride (SiON) as the optically guiding core layer, a great flexibility in the design of planar optical waveguide structures is obtained as the refractive index of SiON can be varied by changing its nitrogen content. This enables the fabrication of weakly guiding waveguides with an optical mode matched to standard single mode fibers as well as more strongly guiding waveguides for compact integrated lightwave circuits. This technology can also be used as a silicon motherboard for advanced hybrid packages for optical interconnects. As an example, with a refractive index of the SiON core layer of 1.50, waveguide structures with bending radii of 1.5 mm can be achieved. The strength of this planar waveguide technology is illustrated by the example of a thermo-optically tunable space switch that can be used either as a single 1-to-8 switch or multiple parallel 1-to-4, 1-to-3 or 1-to-2 switches.

1. Introduction

For many years, planar optical waveguide structures have been the subject of intense research for applications in the fields of sensors, optical interconnects and optical communications [1-5]. Various optical components are now commercially available in these fields. In conventional approaches, silica is used to form the core and the cladding layers. Doping of the central core layer with P, Ge, or Ti, allows the refractive index of silica to be increased relative to the cladding layers. Typically this relative refractive index contrast is between 0.005 and 0.007, and channel waveguides with very low propagation losses well below 0.1 dB/cm can be fabricated. As the waveguide dimensions are well matched in optical mode to standard single-mode fibers (SSM), low coupling losses of typically 0.1 dB can be achieved.

The radius of curvature of a waveguide bend is determined by the refractive index contrast and is between 15 and 20 mm for the conventional case [1, 2]. The maximum achievable doping concentration limits the index contrast to about 0.01 and the minimum radius to typically 10 mm. Already relatively complex planar lightwave circuits (PLC) will consequently have large chip dimensions, making it problematic to achieve higher integration densities.

Waveguides with greater index contrast can be fabricated by depositing silicon-oxynitride (SiON) as core layer [3-5] by plasma-enhanced chemical vapor deposition (PECVD). The refractive index of the SiON can be varied continuously between the values of silicon-oxide (1.45) and silicon-nitride (1.96) by changing the amount of nitrogen.

2. Planar Waveguide SiON Technology

In our approach, we used SiON with a refractive index of 1.500, i.e., with an index contrast of 0.05. This is achieved by an atomic fraction of 7–8% of nitrogen and results in a minimum bending radius of about 1.5 mm [5, 6]. The ridge-type waveguide channel is formed by reactive ion etching and has a width and height of 3.0 and 1.9 μm, respectively. In Fig. 1 a cross section of the waveguide is shown. The as-grown SiON planar waveguides show high propagation losses caused by the vibrational overtone of the N-H bond. Hydrogen is incorporated during the PECVD deposition due to the gaseous precursors. A loss peak appears at 1508 nm and its tail extends into the third telecommunication window ranging from 1540 to 1570 nm. Annealing the films in a nitrogen atmosphere at 1140 °C reduces the H content of the film and hence the N-H induced absorption loss [7]. At shorter wavelengths, such as around 1310 nm and in the 850 nm regime frequently used for interconnect applications, the N-H absorption loss is not an issue but the waveguide has to be designed with an appropriately smaller

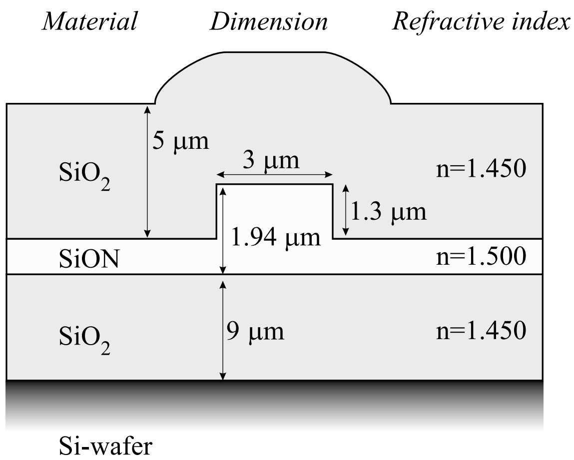

Figure 1. Cross section of the high-index contrast SiON waveguide structure for PLC. Note that all indices are given for a wavelength at 1550 nm.

cross section for single-mode operation. After processing, polarization-insensitive waveguides [8] with low propagation losses of less than 0.15 dB/cm at 1550 nm are obtained [9].

These waveguides have a relatively small geometrical cross section and a high lateral effective refractive-index contrast of 0.02 compared to SSM. For packaging, efficient fiber-butt coupling can be achieved by using short mode converters [10], or commercial small-core fibers with a numerical aperture of about 0.3, which are matched to our channel waveguide. These fibers can easily be spliced to SSM fibers with low excess loss. Deep trenches with vertical sidewalls can be etched by RIE through the full waveguide structure of 15 μm, enabling hybrid integration of other optical components such as nonlinear optical elements or active transmitter or receiver building blocks.

3 Applications of Optical Waveguide Devices

The high-index contrast planar SiON waveguide technology described above has been used to fabricate a variety of devices for applications in the wavelength window around 1550 nm. Add/drop filters for WDM ring networks, which can drop and/or add one wavelength channel optically out of a stream of many wavelengths, have been built in different configurations. 1-from-8 filters with a flat passband and a channel separation of 1.6 nm and 1-from-12 filters with a separation of 1.6 nm have been fabricated [6]. To improve isolation values, a 1-from-4 filter device with a spacing of 1.6 nm has been realized in a special add-after-drop configuration [8, 11]. The WDM filters are formed using the resonant coupler approach, a concatenation of directional couplers and delay lines. Wavelength tuning can be achieved by changing the phase in the delay-line arms by exploiting the thermo-optic effect. Furthermore, flexible thermo-optic space switches, which can be used as a single 1-to-8 switch or in a multiple 1-to-4, 1-to-3, or 1-to-2 configuration, were fabricated for applications in optical interconnects [12, 13]. The SiON waveguides are sensitive to ultraviolet light, which enables the formation of Bragg gratings by direct writing with an excimer laser in our SiON waveguides [14]. Basic studies to realize Bragg grating devices have been done.

Using the example of the thermo-optical space switch, we will illustrate the strengths of the high refractive index contrast technology. The integrated optical switch we implemented resembles an arrayed waveguide grating (AWG) wavelength multiplexer [15]. The geometrical layout is shown in Fig. 2. It consists of a number of input waveguides (typically 8), a star coupler that divides the input light over an array of (typically 16) channel waveguides, and a second star coupler that refocuses the light from the array onto one of the output waveguides. Unlike an AWG, all of the array waveguides have equal lengths and are equipped with individually tunable heaters, which function as phase shifters. By adjusting the phase distribution across the array waveguides we can determine onto which output waveguide the light is refocused and maximize the isolation to the other output waveguides. This thermo-optically induced beam steering enables switching from input signals to the desired output signals in a very flexible way: When light from input channel 4 is focused onto output channel 5, light from input channel 3 will be focused onto output channel 6 and so on (assuming input and output channels numbered 1 to 8, from top to bottom). This allows us to use the same device, for example, as a switch from 1 input to 8 outputs, but also as two parallel 1-to-4 switches, one switch using input 4 with the even outputs and the other using input 5 with the odd outputs. In a comparable manner, four parallel 1-to-2 switches can be defined and, using loopback channels, cyclic switch types are also possible.

The optical switches have been characterized on the chip level using a PC-controlled setup. This system controls both the butt-coupled fiber alignment stages on the in- and out-coupling side of the chip and the individual electrical heaters [13]. To find the optimum heater settings corresponding to the various switch directions, we used an iterative optimization procedure based on a computer algorithm. The resulting heater settings are then stored and can be retrieved when the switch direction must be changed. Such a reconfiguration of the switch takes less than 1 ms. The linear phase gradient needed to switch a center input channel to one of the outer outputs would require a phase shift of more than 9π between the first and the last heater. How-

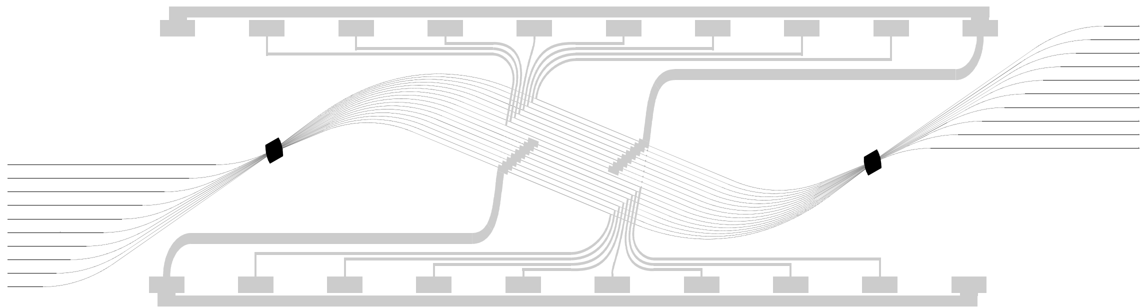

Figure 2. Geometrical layout of the space switch showing the different mask layers (waveguide layer, chromium heater, and aluminum leads). Not to scale.

Table 1. Overview of the thermo-optical switch measurement results

Outputs		Functionality	On-chip loss for center output waveguide		Additional loss for outer output waveguides		Isolation
Used	Design		Measured	Design	Measured	Design	
8	8	1-to-8, 2 × 1-to-4 4 × 1-to-2	5.7 dB	4.0 dB	2.7 dB	1.0 dB	22 dB
6	6	1-to-6, 2 × 1-to-3 3 × 1-to-2	2.4 dB	1.7 dB	2.4 dB	1.0 dB	23 dB
4	6	1-to-4, 2 × 1-to-2	2.4 dB	1.7 dB	1.4 dB	0.4 dB	25 dB
3	6	1-to-3	2.4 dB	1.7 dB	0.9 dB	0.4 dB	29 dB

ever, as the required phase change is periodic with 2π, much lower heater-power distributions are sufficient to reach all switching positions. Experimentally we found that 0.59 W of electrical power is sufficient to induce a phase shift of 2π.

An example of the switching behavior of our devices is shown in Fig. 3. This figure summarizes the optical throughput measurements for the 1-to-8 switch for the case where light at input channel 5 is switched to all possible outputs. The measured optical parameters of this switch are shown in the first row of Table 1. The rest of the table shows the measured properties when 6, 4 or only 3 outputs of a switch designed for 6 outputs are used. The center output channels have better uniformity and crosstalk properties, therefore the switch quality improves when fewer output channels are used.

The results of the measurements on the switches are summarized in Table 1. As can be seen from these results, the device concept allows us to realize a compact versatile switch that performs well when used in a 1-to-8 configuration and even better when limited to a 1-to-6, 1-to-4 or a 1-to-3 switch, but also when used as multiple parallel 1-to-3 or 1-to-2 switches. In addition to such flexibility, this integrated space switch allows the formation of complex switch matrices without the need to cascade 2×2 switches. Increasing the number of array waveguides with heater sections will improve performance by reducing spillover and diffraction losses at the star couplers and improving the power distribution over the output waveguides.

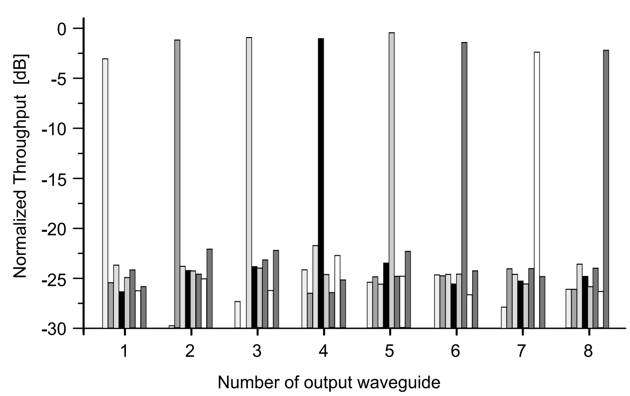

Figure 3. Throughput of the output waveguides for all switch directions of a 1-to-8 switch. The throughput is normalized to output 5. For each output waveguide eight columns are drawn, which show the normalized throughput for this output waveguide for all eight switch settings.

4 Conclusion

Planar waveguide structures formed by layers of SiON and SiO_2 open the way to low-cost mass fabrication of planar lightwave components for a variety of interconnect and optical networking applications. The flexibility in changing the nitrogen content in PECVD deposited silica enables the formation of high refractive index contrast optical waveguides. Choosing an index of 1.500 of the SiON core layer allows the formation of bent structures with radii of 1.5 mm at negligible excess losses. Optical propagation losses in the 1550 nm band can be as low as 0.1 dB/cm after proper deposition and subsequent annealing. The birefringence in the channel waveguides can be controlled accurately such that no polarization sensitivity occurs.

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