RZ 3122 (# 93168) 04/26/99
Physical Sciences 6 pages

Research Report

Silicon-Oxynitride (SiON) for Photonic Integrated Circuits

H.W.M. Salemink, F. Horst, R. Germann, B.J. Offrein, and G.L. Bona

IBM Research Division
Zurich Research Laboratory
8803 Rüschlikon
Switzerland

LIMITED DISTRIBUTION NOTICE

This report has been submitted for publication outside of IBM and will probably be copyrighted if accepted for publication. It has been issued as a Research Report for early dissemination of its contents. In view of the transfer of copyright to the outside publisher, its distribution outside of IBM prior to publication should be limited to peer communications and specific requests. After outside publication, requests should be filled only by reprints or legally obtained copies of the article (e.g., payment of royalties).

IBM Research Division
Almaden · Austin · Beijing · Haifa · T.J. Watson · Tokyo · Zurich

Silicon-Oxynitride (SiON) for Photonic Integrated Circuits

H.W.M. Salemink, F. Horst, R. Germann, B.J. Offrein, and G.L. Bona

IBM Research Division, Zurich Research Laboratory, 8803 Rüschlikon, Switzerland

Abstract

We report on the fabrication and analysis of silicon-oxynitride (SiON) as core material for silicon-based planar photonic waveguide circuits. Features of devices made of this particular SiON material are: (1) a silicon-compatible technology (low-cost perspective), (2) a waveguide structure with high dielectric index contrast, allowing a very compact device layout (approximately 10× smaller radius of curvature than conventional doped SiO_2 technology), (3) a low optical loss < 0.15 dB/cm, in the 1550 nm telecommunication window and (4) a negligible polarization dependence. The materials aspects and resulting analyses of the SiON layers as well as particular device properties are described.

I. INTRODUCTION

Analogous to fiber devices in optical telecommunication systems, silicon-based photonic integrated circuits (PICs) have been actively pursued: the silicon-based fabrication, processing, and replication technology lends itself to mass production and is hence low-cost. Most notable in this area is the work on doped SiO_2 glass by the NTT and Lucent groups [1,2] using either flame-hydrolysed or LPCVD-deposited doped-glass devices. These low-doped glassy waveguide structures are very similar to well-known waveguiding glass fibers with respect to optical guiding (index contrast between core and cladding layers) and hence have very similar modal fields resulting in low coupling losses between the chip and standard single mode fiber. An inherent disadvantage of these low index-contrast glassy structures is the rather large radius of curvature allowable in circuits, typically greater than 10 mm [1]. We report on silicon-oxynitride (SiON) as an alternative silicon-based oxide for waveguide devices [3]. Owing to the nitrogen "doped" silicon-oxide compound, the dielectric value (refractive index) can be adjusted in a very flexible way to match other design criteria such as, e.g., achievable dimensions. In the work reported here, a relatively high effective lateral contrast in refractive index of 0.02 between the SiON (waveguiding) core layer and its surrounding (lower and upper) SiO_2 cladding layers is used (Fig. 1). This index contrast is approximately 10$\times$ higher than usual for Ge-doped SiO_2 waveguides [1,2] and allows a 10$\times$ smaller radius of curvature (1.5 mm) to be used in our circuit layouts. The higher areal density results in a much more economical usage of wafer area and allows us to design multi-stage filter devices on 85 mm of chip length [4]. The high propagation loss at 1550 nm wavelength, usually associated with SiON compounds [5], is decreased to a value of 0.10 to 0.15 dB/cm via a high-temperature anneal process. By properly adjusting the mechanical film stress in the oxidic trilayer, a negligible polarization sensitivity of $\leq$ 0.05 nm is obtained in channel waveguide filters.

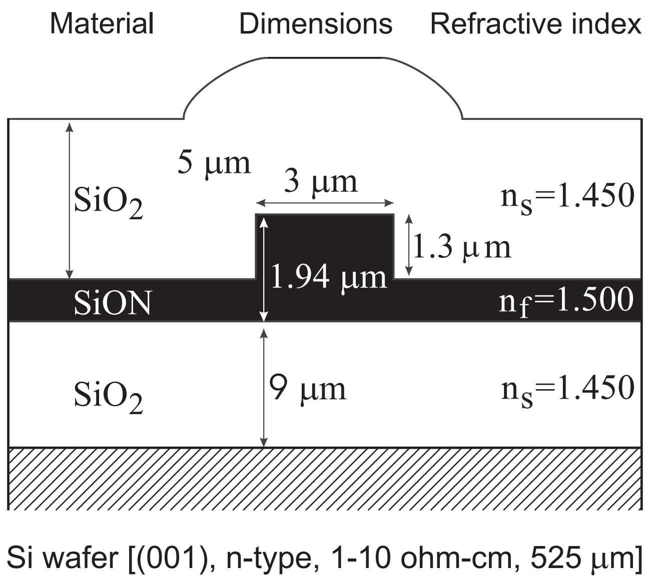

FIG. 1. Schematic view of SiON/SiO_2/Si waveguide structure.

II. EXPERIMENT

A. SiON material deposition, analysis and control

As base material, single-side polished, 4″ p-type silicon (001) wafers with a resistivity of 3-5 Ohm-cm are used. The lower SiO_2 cladding layer is thermally grown by wet (or pyrogenic) oxidation at temperatures of 1050 to 1150 °C (the 8.5-μm-thick thermal oxidation on Si, has been provided by Vegatec, Rousset, France). The SiON core layer is deposited at a temperature of 400 °C using PECVD in an RF plasma, with gaseous precursors of SiH_4, N_2O and NH_3 as described in [6]. This particular SiON process has been selected for reasons of better index control out of a matrix of experiments with LF or RF plasma frequencies and with or without the NH_3 precursor. The use of three precursors allows a final adjustment of the SiON index around a value of 1.500 with an accuracy of 5×10^{-4}. In order to achieve an effective lateral index contrast of 0.02 for the guiding mode in the ridge-type structure as sketched in Fig. 1, the refractive index of the SiON has to be 0.05 higher than that of the surrounding SiO_2. Our SiON material is designed to have an index of 1.500 around 1550 nm and 1.510 nm when measured at 632 nm. Subsequent to the SiON core deposition, a high-temperature anneal process is performed, mainly to reduce the hydrogen-related losses in the core [5]. The use of hydrogenated precursors for SiON and SiO_2 and the relatively low deposition temperature both lead to the incorporation of appreciable amounts of hydrogen into the oxidic films, either bonded as N-H, O-H, Si-H, or as excess hydrogen. The FT-IR spectra (Fig. 2) of the as-deposited SiON layers readily show the N-H vibrational bond near wave number 3382/cm. The first overtone of this frequency results in an excess N-H-related absorption loss at a wavelength of 1510 nm, extending into the optical operating window of 1540-1560 nm of the final devices. Following SiON core annealing, optical lithography and reactive ion etching (RIE) are used to define the desired ridge structure, and the 5-μm-thick SiO_2 upper cladding is deposited with PECVD [6].

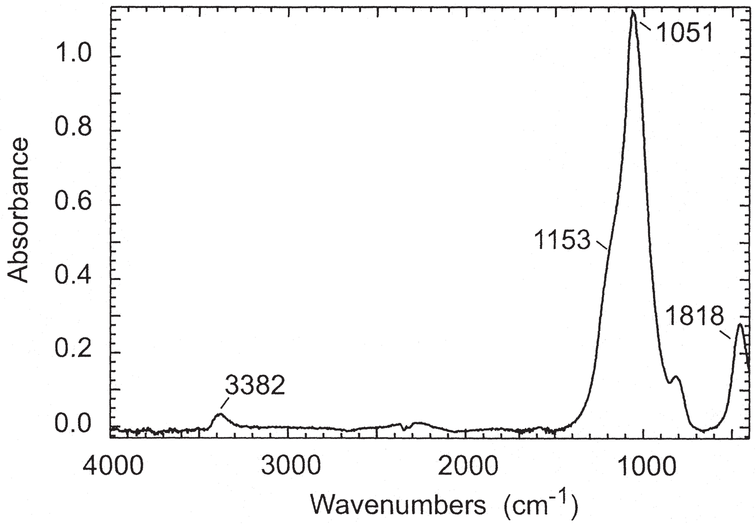

FIG. 2. FT-IR spectrum of as-deposited SiON layer on Si: note the isolated N-H vibrational bond at wave number 3382/cm. Other peaks are well-known SiO vibrational modes near 1050/cm. Upon annealing at 1145 °C in nitrogen atmosphere, the N-H peak at 3382/cm is removed from the IR spectra. See also Fig. 3.

B. SiON slab layers

The first overtone of the N-H IR vibrational mode at 3382/cm peaks at a wavelength of 1510 nm and its Lorentzian tail extends into the operating window of the photonic devices (1540-1560 nm) as required by the erbium optical amplifiers. The slab propagation loss in 2.0-μm-thick, as-deposited SiON films onto 8.5-μm-thick SiO_2 amounts to more than 1.0 dB/cm at 1550 nm wavelength, as measured via a moving prism coupling technique and a tunable laser source. After annealing for 2.5 h in a nitrogen atmosphere at 1145 °C, the reduction in the density of N-H bonds results in a tenfold improvement (decrease) of the slab loss as shown in Fig. 3. Typical peak loss at 1510 nm is 1.0 ± 0.2 dB/cm and 0.10 ± 0.05 dB/cm at 1550 nm. The lower limit and accuracy of this dual prism loss measurement is estimated at 0.05 dB/cm. The detailed temperature dependence of the N-H removal as a function of temperature will be published separately. Note that the residual N-H contribution at our normal anneal temperature of 1145 °C still leads to an N-H related excess loss of 0.10 dB/cm in the Lorentzian tail at 1535 nm, on top of any background loss at 1550 nm. The high-temperature anneal cycle results in hydrogen removal: in addition, SiON layer compaction occurs, measured with an ATR technique (attenuated total reflection) [7] on 2.0-μm-thick SiON layers deposited onto silicon. Upon annealing of the SiON compositions of interest here, the film thickness decreases by a factor of 0.93 and the refractive index increases as shown in Fig. 4. The required final index of SiON is obtained with an accuracy of 5×10^{-4}. Rutherford backscattering (RBS) has been used to determine the SiON layer composition, as-deposited and after annealing at 1145 °C: the results are listed in Table 1. The hydrogen fraction (bound as N-H, O-H, Si-H or in excess) is largely reduced to the detection limit of 0.01 upon annealing at 1145 °C. As the high-temperature treatment is successful in reducing the N-H content, it presumably also rapidly reduces the weaker O-H bond contributions in the film [5].

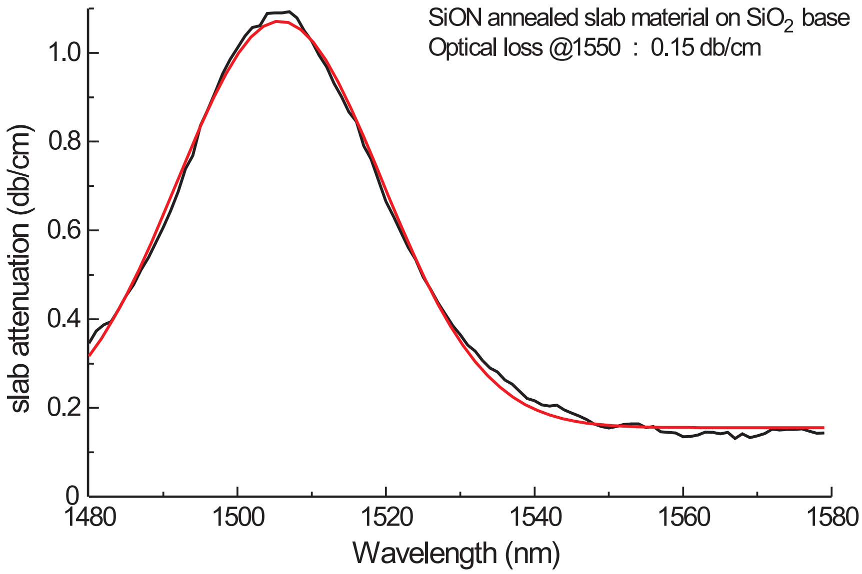

FIG. 3. Optical propagation loss in SiON slab layers after annealing as measured with a dual (moving) prism coupling technique. The SiON layers of 2.0μm thickness are grown onto 8.5μm thick thermal SiO_2. Prism separation is adjusted from 10 to 25 mm. The smooth line is a Lorentzian fit to the experimental curve. Typical optical loss data are 1.0 ± 0.2 dB/cm at 1510 nm and 0.10 to 0.15 dB/cm at 1550 nm.

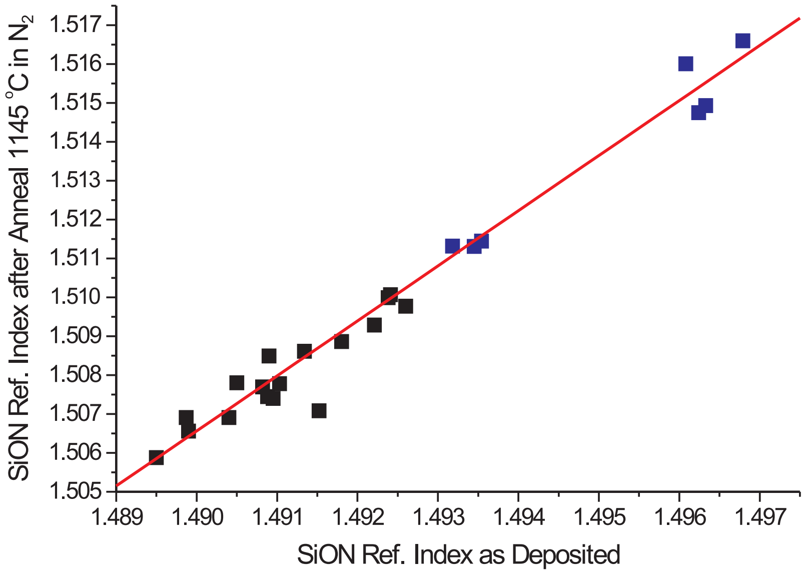

FIG. 4. Refractive index of 2.0-μm-thick SiON layers on silicon, measured with the ATR technique, showing the index increase upon annealing. The symbols represent different SiON films out of a large dataset of SiON layers. Horizontal scale: index of as-deposited films; vertical scale: index of annealed films.

C. SiON waveguide devices

Loss data have been obtained on completed waveguide channels (as sketched in Fig. 1) using two mask sets. The first set uses meanders with various overall lengths of between 70 and 170 mm, all with a 5-mm radius of curvature: the transmitted optical power is plotted on semi-log graphs as a function of waveguide length, and loss is determined from the slope of the graph. This layout consumes a large area on the 4″ wafer, the technique is affected by individual defects and inhomogeneities. The second mask set is based on ring resonators, and loss is determined from its finesse [8]. This technique has the advantage of consuming only a small wafer area and of delivering reliable loss data with a high accuracy of 0.01 dB/cm. With the second technique, loss values have been repeatedly measured to be below 0.10 dB/cm at 1550 nm wavelength, after annealing, for several SiON growths [9].

TABLE I. RBS analysis of SiON layers, as-deposited and annealed (RBS analysis performed by CAFI, LeLocle, Switzerland).

Element	as-deposited	annealed
Si	1.0	1.0
O	1.90	1.90
N	0.07	0.08
H	0.16	<0.01

estimated accuracy: ± 0.01

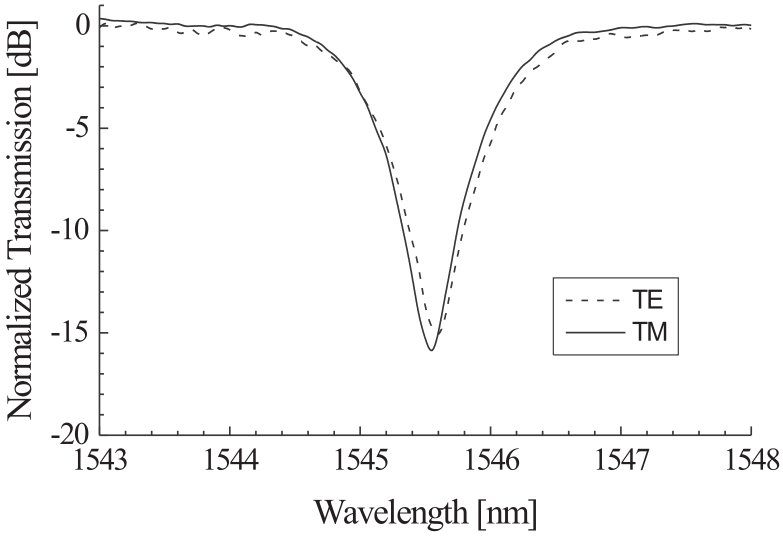

FIG. 5. Negligible polarization sensitivity ($\leq$ 0.05 nm between TM and TE modes) for complete waveguide devices after additional thermal processing to minimize the stress-induced birefringence.

D. Birefringence and stress control

The birefringence (index difference between TM and TE mode) in our trilayer oxidic stack on silicon has two origins: (1) the geometrical birefringence due to the designed ridge geometry and (2) a stress-induced component due to different thermal expansion coefficients of SiO_2, SiON, and silicon and the various (process) temperatures. The second effect is more difficult to estimate, regarding the widely scattering data from the various SiO_2 fabrication techniques. A pragmatic approach is taken for optimization of the stress-induced birefringence. By appropriate thermal processing of the complete trilayer waveguide, a negligible polarization sensitivity of $\leq$ 0.05 nm between TM and TE nodes is obtained (Fig. 5).

III. CONCLUSIONS

The use of SiON material as waveguiding core layer in SiO_2-based photonic devices is discussed. The material is chosen to obtain a high core index of 1.500 and relatively high effective optical contrast of 0.02, allowing a 1.5-mm radius of curvature. Key issues for optimization of the SiON material include annealing to remove N-H bonds and to obtain low optical loss of $< 0.10 \pm 0.05$ dB/cm at 1550 nm. Refractive index control is shown to be $\pm 5 \times 10^{-4}$ at a value of 1.500, after annealing at 1145 °C. Appropriate thermal treatment leads to negligible polarization sensitivity of $\leq$ 0.05 nm at the 1550-nm wavelength in devices. The SiON/SiO_2 oxide waveguides offer a perspective for a high-density layout of photonic integrated circuits.

IV. ACKNOWLEDGMENT

We gratefully acknowledge the support of R. Beyeler, U. Drechsler and M. Tschudy. Part of this work was supported by the ACTS COBNET AC069 EU-consortium. We acknowledge helpful discussions with G. Lucovsky on the SiON compositions.
Corresponding author: H. Salemink (smk@zurich.ibm.com)

V. REFERENCES

---

[1] M. Kawachi, Opt. and Quantum Electronics **22**, 391-416 (1990).

[2] Y.P. Li and C.H. Henry, IEE Proc. Optoelectronics, **143**, 263-280 (1996).

[3] M.R. Paiam, C.F. Janz, R.I. MacDonald, J.N. Broughton, IEEE Photon. Technol. Lett. **7**, 1180-1182 (1995).

[4] B.J. Offrein, G.L. Bona, F. Horst, H.W.M. Salemink, R. Beyeler, R. Germann, IEEE Photon. Technol. Lett., **11**, 239-241 (1999).

[5] F. Bruno, M.D. Guidice, R. Recca, F. Testa, Appl. Optics, **30**, 4560-4564 (1991).

[6] R. Germann, H.W.M. Salemink, R. Beyeler, G.L. Bona, I. Massarek, F. Horst, B.J. Offrein, Proc. of 195th Meeting of the Electrochemical Soc., Seattle, WA, May 1999; G.L. Bona, W.E. Denzel, B.J. Offrein, R. Germann, H.W.M. Salemink, F. Horst, Opt. Engineering **37** 3218-3228 (1998).

[7] H.E. de Bruijn, R.P.H. Kooyman, J. Greve, Appl. Optics **29**(13) (1990).

[8] F. Horst, H.W.M. Salemink, R. Germann, B.J. Offrein, G.L. Bona, Proc. IEEE/LEOS Benelux Chapter, 33-36 (1998).

[9] H.W.M. Salemink, F. Horst, B.J. Offrein, R. Germann, G.L. Bona (in preparation).