Metallic-Contamination-Induced Optical Loss in Silicon Microphotonic Waveguides.

Tymon Barwicz[†], Charles W. Holzwarth, Peter T. Rakich, Milos A. Popovic, Erich I. Ippen, and Henry I. Smith

Research Laboratory of Electronics, Massachusetts Institute of Technology, 77 Massachusetts Ave, Cambridge, MA 02139 USA
[†]Current address: IBM T.J. Watson Research Center, Yorktown Heights, NY 10598 USA
tymon@us.ibm.com

Abstract: We report on optical loss reaching 100 dB/cm observed in Si wire waveguides defined by reactive-ion etching in the proximity of metals with a low temperature of silicide formation.

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1. Introduction

Single-crystal silicon is a prime material for microphotonics. Being the workhorse of the microelectronics industry, Si is widely available and its properties well understood. Nonetheless, propagation losses in silicon wire waveguides are not fully understood. Most often, scattering loss [1] and bulk material absorption cannot fully account for the measured propagation loss and other loss mechanisms, such as electronic absorption via surface states, have been investigated [2]. Here, we describe a loss mechanism in Si waveguides that, to our knowledge, has not yet been addressed in the literature.

We report on optical loss reaching 100 dB/cm in Si waveguides patterned via reactive-ion etching (RIE) in proximity of metals such as Ni, Pd, or Co. Such optical loss was not observed in waveguides patterned in proximity of metals such as Fe, Cr, or Ti. The experimental results point towards silicide formation at the waveguide sidewalls as the cause of the optical loss. The silicide forms without contact between the metal layer and the Si. It is the sputtered metal atoms that react with the Si surface. In fact, a sub-nanometer layer of silicide at the waveguide sidewalls is sufficient to account for the observed loss. Even when very thin, such silicide is difficult to remove.

The relevance of this loss mechanism goes beyond the case of a metal layer in close proximity to a Si waveguide being etched. Metallic contamination can readily occur at a lesser degree than what is experimentally investigated in this paper. For instance, RIE chambers are often built of stainless steel that contains Ni, and traces of nickel silicide have been shown to form on bare Si wafers at etching [3]. Hence, the possibility of a silicide layer contributing to observed losses in general Si waveguides must be borne in mind.

2. Experiment

300- and 450-nm-wide rectangular Si waveguides were fabricated with e-beam lithography on thermally oxidized silicon-on-insulator (SOI) wafers using a process similar to the one described in [4]. A 50-nm layer of metal was evaporated on the patterned e-beam resist and lifted off. The metal was then used as a hardmask for RIE before being thoroughly stripped via wet processing. This approach is commonly used for circumventing the weak etching resistance of most e-beam resists. Fig. 1 illustrates the material stack during RIE. A Plasmatherm 790, a conventional RIE system, was used at a pressure of 10 mT and a bias of 500 V. A gas flow of 17 sccm of CHF_3 was used for etching the top layer of SiO_2 and 60 nm into the thick SiO_2 on the bottom of the stack. A gas flow of 13.5 sccm of CF_4 and 1.5 sccm of O_2 was used to etch the Si.

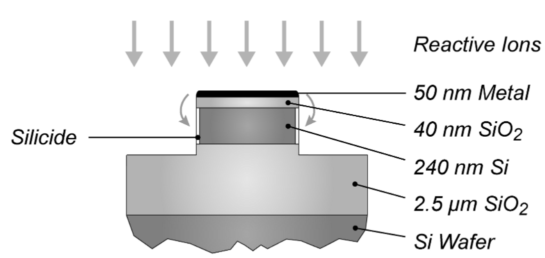

Fig. 1 Illustration of the mechanism to which the optical loss is attributed. At reactive-ion etching, sputtered metal atoms react with the silicon sidewall to form a silicide. The silicide is difficult to remove and induces an optical loss that is comparable to loss induced by a metal. The metal hardmask was thoroughly stripped before optical characterization.

Table 1. Transparency of waveguides etched with various metal hardmasks.

Metal	Ni	Pd	Co	Fe	Fe-Ti	Cr
Silicide Formation Temperature	200ºC	350ºC	375ºC	500ºC	450ºC (Ti)	450ºC
Waveguide Transparency	No	No	No	Yes	Yes	Yes

The waveguide transparency was assessed by measuring the transmitted optical power through 2- to 4-mm-long straight waveguides at wavelengths ranging from 1430 to 1610 nm. Table 1 summarizes the experimental results and shows the silicide formation temperatures for the metals investigated. The attenuation of the fundamental mode was 20 to 30 dB greater in waveguides considered not transparent than in waveguides considered transparent. This corresponds to excess optical loss reaching 100 dB/cm. Table 1 shows that metals inducing high optical loss have a low temperature of silicide formation. This suggests that a silicide forms during RIE, in spite of the metal layer and the Si not being in contact. This was reinforced by inspecting the Pd sample with a scanning transmission electron microscope (STEM) equipped with an energy dispersive x-ray spectrometer (EDS). The results are shown in Fig. 2. Pd was detected in the silicon waveguide at 1-2 nm from the sidewall but not at 8-9 nm from the sidewall. To estimate the optical loss resulting from a silicide layer at the sidewalls, we performed a vectorial mode solver analysis assuming that the thin silicide retained the published optical properties of bulk silicide [5]. We found that the optical loss would be of the order of 10,000 dB/cm per nanometer of nickel silicide at the waveguide sidewalls. Hence, a silicide layer with an average thickness of the order of 0.01 nm would account for the observed loss.

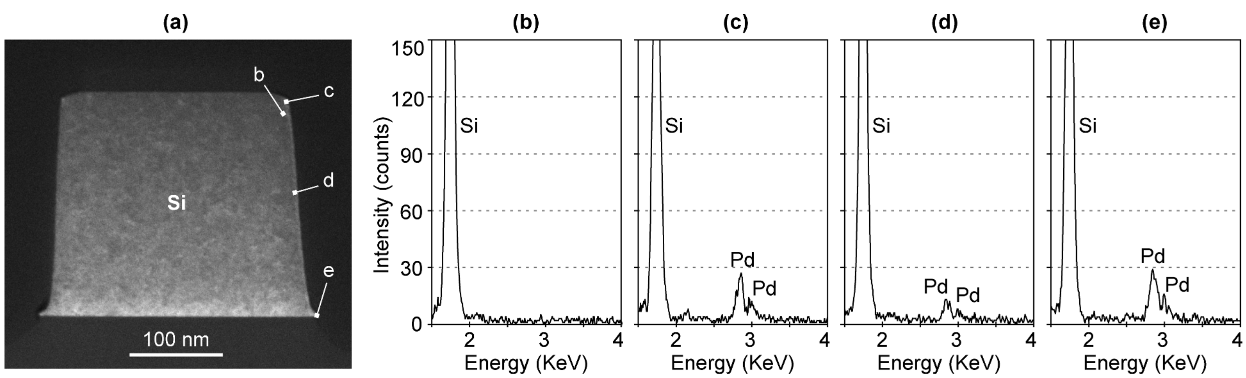

Fig. 2 STEM-EDS analysis of a Si waveguide etched in proximity of Pd and thoroughly cleaned with wet chemical processing. (a) Cross-sectional micrograph indicating where the EDS spectra were acquired. (b) EDS spectrum acquired 8-9 nm from the waveguide sidewall showing no detectable Pd. (c)-(e) EDS spectra acquired 1-2 nm from the waveguide sidewall showing the presence of Pd.

3. Conclusion

We report on strong optical loss in silicon wire waveguides etched in proximity of metals with a low temperature of silicide formation. The experimental data indicates thin silicide formation at the waveguide sidewall as the cause of optical loss despite the lack of direct contact between the Si and the metal layer. This was reinforced by STEM-EDS inspection showing the presence of metal at the waveguide sidewall despite thorough wet chemical cleaning. This loss mechanism is an important consideration for achieving low optical loss in Si waveguides and resonators.

4. References

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