## Low-loss, Nonlinear $BaTiO_3$-Si-Photonic Waveguide Structures

**F. Eltes**[1]*, D. Caimi[1], F. Fallegger[1], M. Sousa[1], E. O'Connor[1], M. D. Rossell[2], B. Offrein[1], J. Fompeyrine[1], and S. Abel[1]

[1]IBM Research – Zurich, Säumerstrasse 4, 8803 Rüschlikon, Switzerland
[2]Electron Microscopy Center, EMPA, 8600 Dübendorf, Switzerland

*fee@zurich.ibm.com

Barium titanate ($BaTiO_3$) has become an attractive material to extend the functionalities of the silicon photonics platform because of its large Pockels coefficient of more than 1000 pm/V. $BaTiO_3$ integrated epitaxially on silicon-on-insulator (SOI) substrates, using $SrTiO_3$ seed layers, can be structured in active and passive silicon photonic devices using slot-waveguide geometries (Fig. 1a). However, all devices demonstrated so far suffer from high optical propagation losses of ~40 – 600 dB/cm [1,2,3], which limits their performance compared with state-of-the-art silicon photonics devices (< 2 dB/cm). Reported losses of 4 dB/cm in waveguides fabricated made from $BaTiO_3$ layers deposited on magnesium oxide substrates [4] indicate that $BaTiO_3$ thin films do not suffer intrinsically from high propagation losses. In this work, we carefully studied various contributions to the propagation losses in hybrid $BaTiO_3$/Si waveguides to ultimately identify and eliminate the reason for the losses. In particular, we used various waveguide geometries, process conditions, and post-fabrication annealing treatments to separate loss channels arising from scattering and absorption in the different materials and at their interfaces. We measured the propagation losses at various steps during the fabrication of the slot waveguides, using $SiO_2$ strip-loaded waveguides (Fig. 1b).

We identified a strong optical absorption of more than 10,000 dB/cm in the thin $SrTiO_3$ seed layer as the major source of these large propagation losses. When manufacturing slot-waveguide structures, the $BaTiO_3$/$SrTiO_3$ layer stack is typically exposed to hydrogen during integration of the top silicon layer, which is done by either direct wafer bonding or chemical vapor deposition. Control experiments together with X-ray photoelectron spectroscopy confirm that the hydrogen is incorporated in the $SrTiO_3$-layer making it absorbing. In contrast, absorption effects in the $BaTiO_3$ layer are negligible.

We demonstrate that a low-temperature anneal is sufficient to remove hydrogen and to achieve low propagation losses in waveguides. This annealing process allowed us to fabricate $BaTiO_3$-Si waveguides with only 6 dB/cm propagation losses. Low-loss ring resonators with a radius of 75 µm with well-defined resonances and a quality factor of Q > 20,000 (Fig. 1c) demonstrate the usability of the $BaTiO_3$-Si hybrid waveguides. Thus, we found a way to eliminate the previously observed showstopper for incorporating functional and highly nonlinear $BaTiO_3$ films in silicon photonic structures, ultimately enabling ultra-high-speed switches and novel nonvolatile optical devices.

### References

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### Figures

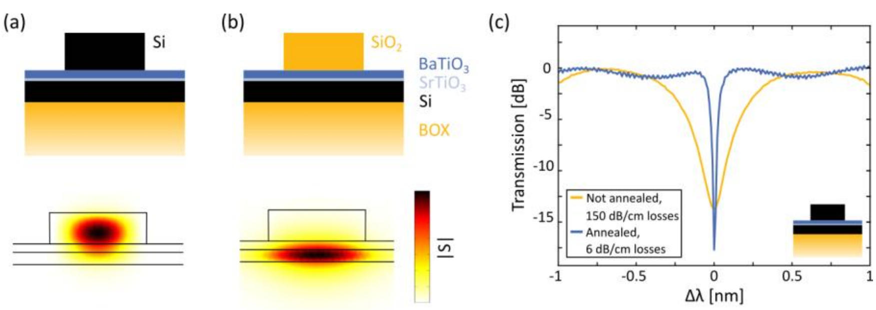


Figure 1: Schematics of (a) the cross section of the target slot-waveguide geometry, and (b) the SiO2 strip-loaded waveguide geometry that was used to investigate partially processed structures. For comparison, the magnitude of the Poynting vector of the optical modes is shown. (c) Comparison of ring resonator (ø 75 µm) spectra before and after annealing. The inset shows the waveguide cross section.