

Second-order nonlinear optics in CMOS silicon

David Heydari[1,*], Mircea Cătuneanu[2,*], Edwin Ng[3,1,*], Jatadhari Mishra[1], Ryan Hamerly[3,4], Dodd J. Gray, Jr.[4], Marc Jankowski[3,1], Martin M. Fejer[1], Hideo Mabuchi[1], and Kambiz Jamshidi[2]

[1]*E. L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA*
[2]*Integrated Photonics Devices Group, Chair of RF and Photonics, Technische Universität Dresden, 01069 Dresden, Germany*
[3]*Physics & Informatics Laboratories, NTT Research Inc., Sunnyvale, CA 94085, USA*
[4]*Research Laboratory of Electronics, MIT, 50 Vassar Street, Cambridge, MA 02139, USA*

Email: dheydari@stanford.edu
[*]*These authors contributed equally to this work.*

Abstract: We demonstrate electric-field-induced second-harmonic generation from 2.4 µm to 1.2 µm in 3 µm-thick silicon ridge waveguides integrated with alternating p-n diodes. Second-harmonic generation as a function of fundamental wavelength tuning is characterized.

OCIS codes: 190.0190, 130.3060, 130.5990

Silicon is a popular material for photonics because of its favorable optical properties in the telecom and mid-wave IR bands, as well as access to wide range of CMOS foundry processes. Along with its widely used nitrides and oxides, however, silicon possesses crystalline inversion symmetry, which precludes it from natively exhibiting second-order nonlinear optical processes. Here, we demonstrate second-harmonic generation using silicon-on-insulator waveguides fabricated in a commercial foundry. The approach used here builds on recent work in silicon photonics that leverages large bias fields to break this material symmetry, thereby enabling $\chi^{(2)}$ interactions. Recently, reverse-biased electric fields integrated into nanophotonic waveguides have been used to break this symmetry, inducing an effective second-order susceptibility from the native third-order susceptibility [1]:

$$\chi^{(2)}_{\text{eff}} = 3\chi^{(3)} E_{\text{DC}} \tag{1}$$

This induced $\chi^{(2)}$ scales proportionally with the reverse-bias DC voltage, up until breakdown occurs between the diodes along the waveguide length. The diodes also aid in sweeping out free-carriers generated by two-photon absorption [2]. In silicon nanophotonics, these electric fields can be generated using ion-implanted p-i-n diodes, and the placement of these diodes can be precisely patterned to achieve poling periods that allow for efficient phase matching of the interacting waves. Such poling is conventionally done one-way, without interchanging the polarity of the diodes [1]. However, in one-way poling, the sign of $\chi^{(2)}$ does not change between adjacent diodes, and at smaller poling periods, there can be residual fringing fields between adjacent diodes which limit the achievable modulation contrast in $\chi^{(2)}_{\text{eff}}$. These issues can be mitigated by interchanging the diodes midway between poling periods, which in principle can quadruple the conversion efficiency (see Fig. 1(b)) [3]. We designed and commercially fabricated silicon nanophotonic waveguides with two-way poling, which demonstrated electric-field-induced, phase-matched second-harmonic generation.

The waveguides, partially shown in Fig. 1(a), were fabricated at a commercial foundry (VTT) specialized in processing 3 µm-thick silicon. The present set of waveguides were nominally designed with a ridge width of 2.75 µm, an etch depth of 1.2 µm, poling period of 11.18 µm, and length of 8 mm. The mid-wave infrared was chosen as the design wavelength for these devices, as this regime mitigates absorption of the fundamental harmonic in the oxide and neighboring dopants in the diodes while also allowing access to shorter second-harmonic wavelengths, which increases the nonlinear conversion efficiency. We operate the diodes at a reverse-bias voltage of 16 V, which induces the generation of second harmonic light. At this bias, we estimate free-carrier lifetimes of approximately 30 ps [2].

Most standard silicon photonics processes use 220 nm-thick silicon. By increasing the thickness of the top layer to 3 µm, the dispersion of the waveguide modes (see Fig. 1(c)) approaches that of bulk silicon, resulting in comparatively larger poling periods. Additionally, better modal confinement in the core leads to lower scattering loss due to sidewall roughness—a critical figure of merit for $\chi^{(2)}$ nonlinear optics, where the conversion efficiency scales quadratically with length—while simultaneously reducing oxide cladding losses for mid-infrared applications [4].

After fabrication, the chips are wire-bonded and packaged to allow external control of the reverse bias voltages. For optical characterization, a lensed fiber is used to couple in fundamental harmonic light from a widely-tunable