Record High Pockels Coefficient in PIC-Compatible $BaTiO_3$/Si Photonic Devices

F. Eltes[(1)]*, J. E. Ortmann[(1,2)], D. Urbonas[(1)] , D. Caimi[(1)], L. Czornomaz[(1)], C. Mai[(3)], L. Zimmermann[(3)], J. Fompeyrine[(1)], S. Abel[(1)]

[(1)] IBM Research – Zurich, Säumerstrasse 4, 8803 Rüschlikon, Switzerland, *fee@zurich.ibm.com
[(2)] Department of Physics, The University of Texas at Austin, Austin, TX, USA
[(3)] IHP, Im Technologiepark 25, 15236 Frankfurt (Oder), Germany

Abstract *We unambiguously demonstrate the Pockels effect in integrated $BaTiO_3$/Si devices and report the largest Pockels coefficient (r_{42}=923 pm/V) of any thin-film material. We show a strong electro-optic response beyond 25 GHz and monolithic integration compatible with silicon photonic platforms.*

Introduction

Electro-optic modulators exploiting the Pockels effect in bulk $LiNbO_3$ have become the backbone of long-haul telecommunications. However, for short-reach optical links, integrated silicon photonics is predicted to be the dominating technology. Due to the lack of a Pockels effect in silicon, various approaches have been explored to bring electro-optic modulators to silicon photonics platforms. Currently available technologies rely either on the plasma-dispersion effect or the Franz-Keldysh effect. The downside of these effects compared to the Pockels effect is a coupled modulation of both phase and amplitude of the optical signal. Hence, pure phase shift modulation cannot be achieved, as is desired for higher order modulation formats. There have been attempts to bring materials with the Pockels effect onto silicon platforms, such as silicon-organic-hybrid (SOH) devices[1], PZT-based devices[2], or thin-film $LiNbO_3$ devices[3]. The use of these materials for monolithic circuits has so far been limited by incompatibility of the integration schemes. $BaTiO_3$ has appeared as a promising candidate for a material with a large Pockels coefficient and suitable for monolithic integration. Because $BaTiO_3$ can be deposited epitaxially on Si substrates, it can be scaled to large wafer sizes. High-speed electro-optic modulators have been demonstrated in $BaTiO_3$ thin-films on exotic oxide substrates[4], and first electro-optic devices on silicon have been demonstrated[5]. In previous work, we also showed an integration route of $BaTiO_3$ devices on a silicon photonics platform[6]. However, up to now, no evidence of a Pockels effect in such structures and no quantitative analysis of the electro-optic effect has been reported.

Here, we present a clear proof of the Pockels effect in electro-optic devices based on $BaTiO_3$ on silicon. Using a variety of device configurations, we extract the highest reported Pockels coefficient (r_{42} = 923 pm/V) of any thin-film. We also confirm the path of monolithic integration of such hybrid $BaTiO_3$/Si devices on advanced silicon photonics integrated circuits (PIC)[6].

Device Structure

The fundamental element of our devices is a strip-loaded waveguide made from 100-nm-thick Si layer on top of 225-nm-thick $BaTiO_3$ on a thick (~2 um) SiO_2 layer (Fig. 1a). The $BaTiO_3$ was deposited by MBE on a SOI wafer with a 100-nm-thick device Si layer. The $BaTiO_3$ and device Si layers were then transferred by direct wafer bonding onto another Si wafer with a thick thermal oxide. After removal of the donor wafer

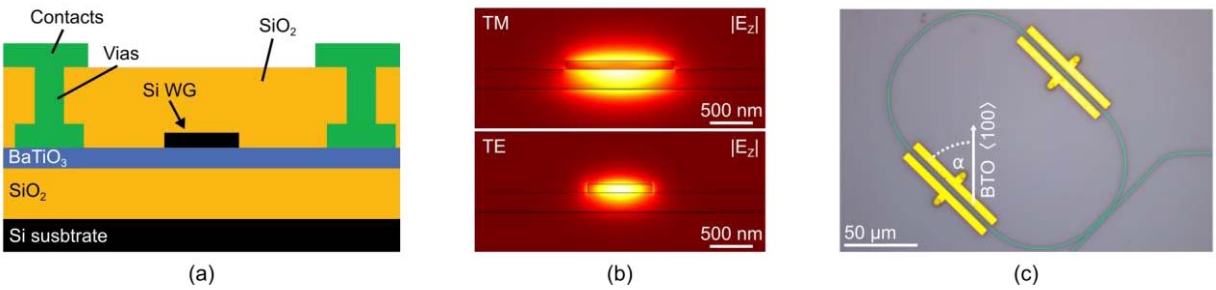


Fig. 1: (a) Schematic cross-section of the $BaTiO_3$/Si phase shifter waveguides. A silicon strip guides the optical mode between two lateral electrodes, which create an in-plane electric field is applied across the $BaTiO_3$. (b) Simulated optical modes showing the fundamental TM and TE mode of the respective waveguide geometry. (c) Top-view image of a racetrack resonator before the top contact level. Racetrack resonators were used to study the orientation dependence of the electro-optic response by varying the angle α relative to the crystal axes of the epitaxial $BaTiO_3$.

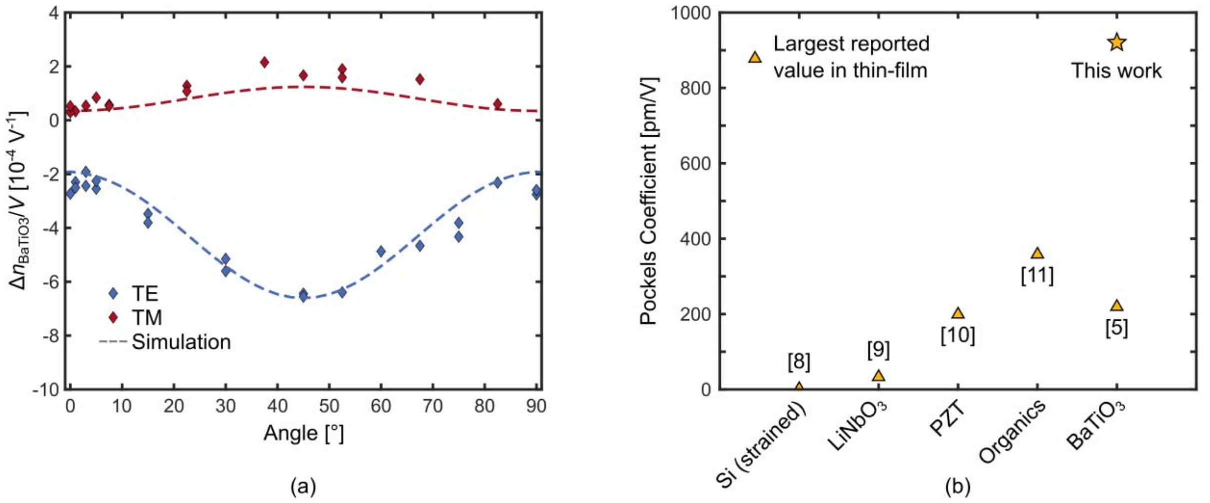


Fig. 2: (a) Electro-optic response of $BaTiO_3$/Si devices as a function of device orientation for both TE and TM devices. An angle of 0°corresponds to devices with waveguides along the $BaTiO_3$ <100> direction. The large anisotropy is characteristic of the Pockels tensor of $BaTiO_3$. (b) Comparison of the largest reported Pockels coefficients for thin-film materials.

we patterned the Si layer into waveguides. An annealing step ensured low propagation losses[7]. Phase shifters were formed by fabricating electrodes along the waveguide to apply an in-plane electric field. As the $BaTiO_3$ layer is deposited epitaxially, the electro-optic response of the devices is expected to depend strongly on the relative orientation of the applied electric field, the optical field, and the crystal axes. This anisotropy is a key signature of the Pockels effect and has not been previously demonstrated in $BaTiO_3$/Si photonic devices. To probe this anisotropy, we designed two different waveguide geometries to guide the fundamental TE and TM mode, respectively (Fig. 1b), at 1.55 um wavelength. We used racetrack resonators with straight phase shifters along a specific direction, rotated by an angle α relative to the $BaTiO_3$ crystal (Fig. 1c).

Characterization

To characterize the devices, we recorded the transmission spectrum of the resonator while applying a DC bias voltage to the phase shifters. We varied the bias between -5 V and 5 V and tracked the position of a single resonance. From the shift of the resonance wavelength we extracted the change in refractive index of $BaTiO_3$, dn_{BTO}/dV. To probe the expected anisotropy of the Pockels effect in $BaTiO_3$, we measured dn_{BTO}/dV for both TE and TM waveguides oriented with an angle α between 0° and 90° relative to the $BaTiO_3$<100> direction (Fig. 2a).

The magnitude of the electro-optic response strongly depends on the angular orientation of the waveguides, as expected for the Pockels effect in $BaTiO_3$. Also in agreement with our expectations, the sign of the change of the refractive index is different between TE and TM devices, with a lower amplitude for TM compared to TE. To extract values for the Pockels coefficients from our data we performed extensive simulations: By iteratively varying the Pockels coefficients we reproduced the same behaviour as observed in the experiments (Fig. 2a). When performing the simulations, we also account for contributions to the index change from ferroelectric switching, which would otherwise lead to an overestimation of the Pockels coefficients. We find that the experimental results can be reproduced with the Pockels coefficients r_{42} = (923±215) pm/V, and r_{33} = (342±93) pm/V. The third distinct coefficient, r_{31}, is smaller than 100 pm/V, but cannot be determined accurately with the current device geometry. These values represent the largest Pockels coefficient reported for any thin-film material (Fig. 2b)[5,8–11].

The extraction of the Pockels coefficients was performed using DC voltages, and does not

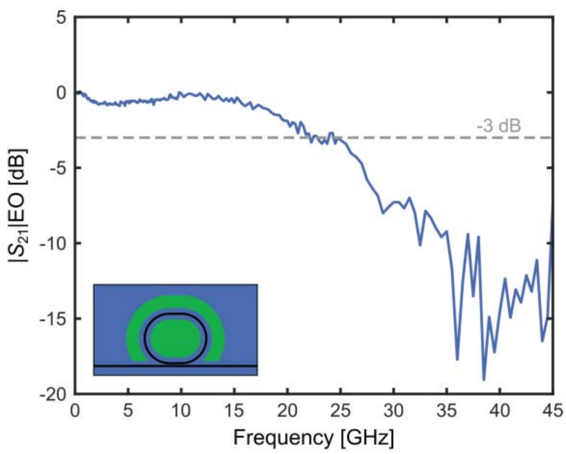
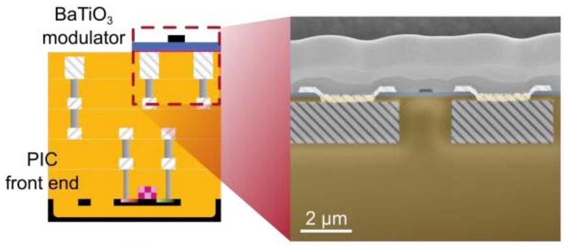


Fig. 3: Electro-optic bandwidth of a $BaTiO_3$ ring modulator. The flat response up to the photon lifetime limited cut-off is characteristic of the Pockels effect. The inset shows the schematic layout of the measured device.



(a) (b)

Fig. 4: (a) Integration scheme for monolithic integration of $BaTiO_3$/Si devices on a Si photonics platform. (b) False-color SEM cross-section of $BaTiO_3$/Si device fabricated on a Si PIC platform.

demonstrate the applicability of $BaTiO_3$ devices for high-speed modulation. To show that electro-optic performance is maintained at high frequencies we measured the S_{21} response of the $BaTiO_3$/Si devices. Because the racetrack resonators have a limited bandwidth due to the high Q-factor (~20'000), we used a small radius (10 µm) ring modulator to increase the device bandwidth. With the ring modulator we can achieve a bandwidth of ~25 GHz (Fig. 3). The bandwidth of the ring modulator is limited by the photon lifetime in the cavity. This limitation can be removed in Mach-Zehnder modulators, as the electro-optic response of the Pockels effect remains constant beyond 100 GHz[12].

Monolithic Integration

The challenges to integrate materials with a Pockels effect have so far been hindering a clear co-development path with advanced silicon photonics platforms. Our devices offer two significant advancements in this respect. First, we deposit the $BaTiO_3$ films on silicon wafers, which is directly scalable to large-size substrates. This is e.g. different to $LiNbO_3$, where the scalability is limited to the availability of $LiNbO_3$ crystals. Second, the fabrication route based on low-temperature wafer bonding is a well-established technique, that can be directly employed for monolithic integration.

As we previously demonstrated[6], wafer bonding of $BaTiO_3$ onto an oxide layer enables integration at any planarized interlayer dielectric (ILD) level in a back-end-of-line (BEOL) process (Fig. 4a). We show such an integration process by transferring a $BaTiO_3$ layer onto a silicon photonics wafer where the BEOL had been interrupted after the 4th metal level followed by a planarized ILD. The successful fabrication of $BaTiO_3$ devices in the BEOL of a silicon photonics platform (Fig. 4b) proves how $BaTiO_3$ can be integrated and packaged, setting it apart from competing material platforms where monolithic integration has yet to be shown.

Conclusions

With our work, we unambiguously demonstrate the presence of the Pockels effect in $BaTiO_3$/Si electro-optic devices and report the largest Pockels coefficients of any thin-film material. We also show that the strong electro-optic response is maintained beyond 25 GHz, highlighting the potential for high-speed modulation. With our integration scheme of wafer-level bonding on ILD layers, we show the applicability of our novel material system in an advanced silicon photonics platform. We believe our work paves the way for monolithically integrated high-speed $BaTiO_3$ devices for a new generation of photonic circuits.

Acknowledgements

We wish to acknowledge funding from the European Commission projects SITOGA, and PHRESCO, from the Swiss State Secretariat for Education, Research and Innovation under contract no. 15.0285, and from the Swiss National Foundation project PADOMO.

References

[1] W. Heni *et al.* Silicon-Organic and Plasmonic-Organic Hybrid Photonics. ACS Photonics **4,** 1576–1590 (2017).

[2] K. Alexander *et al.*, D. Broadband Electro-optic Modulation using Low-loss PZT- on-Silicon Nitride Integrated Waveguides. in *CLEO 2017* JTh5C.7 (2017).

[3] A. J. Mercante *et al.* 110 GHz CMOS compatible thin film $LiNbO_3$ modulator on silicon. Opt. Express **24,** 15590 (2016).

[4] P. Girouard *et al.* $\chi^{(2)}$ Modulator With 40-GHz Modulation Utilizing $BaTiO_3$ Photonic Crystal Waveguides. IEEE J. Quantum Electron. **53,** 5200110 (2017).

[5] C. Xiong *et al.* Active silicon integrated nanophotonics : ferroelectric $BaTiO_3$ devices. Nano Lett. **14,** 1419–1425 (2014).

[6] F. Eltes *et al.* A novel 25 Gbps electro-optic Pockels modulator integrated on an advanced Si photonic platform. in *2017 IEDM* 24.5.1-24.5.4 (2017).

[7] F. Eltes *et al.* Low-loss $BaTiO_3$-Si waveguides for nonlinear integrated photonics. ACS Photonics **3,** 1698–1703 (2016).

[8] P. Damas *et al.* Wavelength dependence of Pockels effect in strained silicon waveguides Opt. Express **22,** 1693–1696 (2014).

[9] H. Lu *et al.* Enhanced electro-optical lithium niobate photonic crystal wire waveguide on a smart-cut thin film. Opt. Express **20,** 2974–2981 (2012).

[10] J. P. George *et al.* Lanthanide-Assisted Deposition of Strongly Electro-optic PZT Thin Films on Silicon: Toward Integrated Active Nanophotonic Devices. ACS Appl. Mater. Interfaces **7,** 13350–13359 (2015).

[11] C. Kieninger *et al.* Record-High In-Device Electro-Optic Coefficient of 359 pm/V in a Silicon-Organic Hybrid (SOH) Modulator. in *CLEO 2017* STu3N.2 (2017).

[12] C. Cochard *et al.*, Broadband characterization of congruent lithium niobate from mHz to optical frequencies. J. Phys. D. Appl. Phys. **50,** (2017).