# Ultra-efficient Optical Switching based on a Large Pockels Effect embedded in Silicon Photonics

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**Abstract:** We have combined BTO with conventional silicon photonic platforms to enhance the performance of silicon photonics by exploiting the Pockels effect. We have demonstrated modulators, switches, and tuning elements with excellent performance exceeding that of silicon-based devices. © 2020 The Author(s)

## 1. Introduction

Integrated photonics is a key technology platform for optical communication, sensing, and data processing. By leveraging existing know-how and infrastructure from the electronics industry, silicon photonics has evolved as a cost effective, scalable technology platform for integrated photonic circuits (PICs). Silicon PICs are used in a multitude of applications ranging from data communications to LIDAR and quantum information processing. Electro-optic modulators, switches, and tuning elements are critical components of PICs in all these applications: Fast and efficient modulators are essential to reach high data rates, low-loss switches are crucial to dynamically reconfigure networks, and low-power tuning elements are important to compensate temperature fluctuations. Today, these components are implemented in silicon photonics by exploiting the plasma-dispersion effect [1] or Joule heating [2], which are, however, intrinsically linked with optical absorption or high power consumption. These challenges could be solved by using the Pockels effect as an electro-optic switching mechanism, offering high-speed operation, low losses, and low static power consumption. However, silicon lacks a Pockels effect which means that new materials with a non-vanishing Pockels effect need to be integrated into silicon photonic platforms to enable Pockels-based electro-optic devices.

Various material platforms have been explored for on-chip applications such as silicon-organic-hybrids (SOH) [3], SiN-PZT [4], or thin-film $LiNbO_3$-on-insulator [5]. Impressive performance of stand-alone devices has been reported using these systems, including record bandwidths and efficiencies. The ambition to take these technologies beyond research demonstrators has so far been limited by integration-incompatibility with large scale silicon photonics production and packaging. $BaTiO_3$ (BTO) has appeared as a promising candidate for a material with a large Pockels coefficient that is suitable for monolithic integration thanks to its composition, its chemical stability, and the possibility to produce it directly on large-diameter silicon wafers [6].

## 2. Integration of BTO with silicon photonics

The production of BTO on silicon substrates allows for the use of large diameter wafers, but it does not necessarily provide a way of integrating BTO into silicon platforms. The BTO deposition takes places at high temperature and

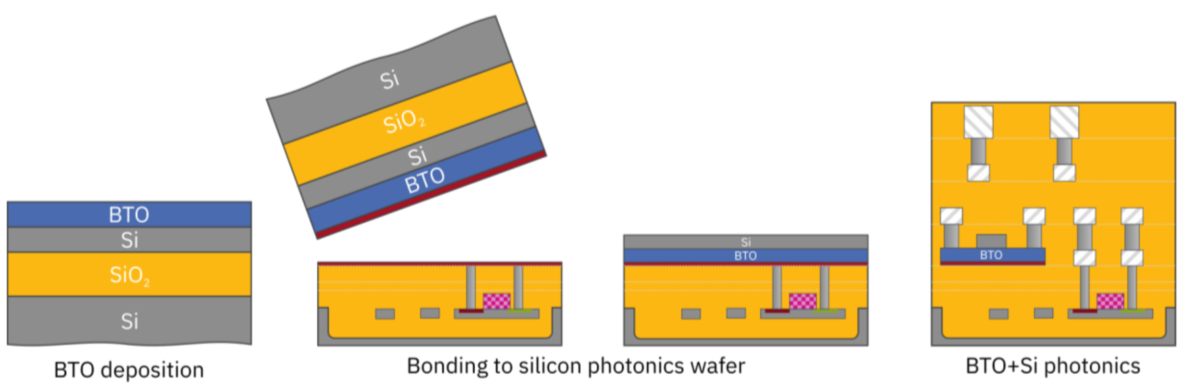


Fig. 1. Concept for integration of BTO with silicon photonics using molecular wafer bonding. BTO is deposited on an SOI wafer and can then be bonded to any wafer with electronic or photonic structures at a planarized level. The donor wafer is removed using mechanical and chemical processes. BTO devices can then be processed along with any back-end-of-line process steps.

requires a high-quality crystalline silicon surface [6], imposing strict requirements on the integration and fabrication of other devices in the platform. As an alternative, we have developed a flexible integration approach based on low-temperature molecular wafer bonding [7]. Using a low-temperature bonding process, the BTO layer can be integrated at any planarized level in a CMOS foundry process, without the risk of exceeding thermal budget restrictions. The first step of this integration process is the deposition of BTO on a SOI wafer, before transferring BTO onto the planarized host wafer using molecular wafer bonding (Fig. 1). The bonding process uses $Al_2O_3$ adhesion layers and includes an annealing at 250°C, well below thermal budgets for both front- and back-end-of-line. We have demonstrated wafer bonding of BTO layers using substrates as large as 200mm (Fig. 2a). Using this process we have successfully integrated BTO devices with silicon photonic platforms without any impact on the standard silicon-based devices [8].

## 3. Performance of BTO-Si devices

Previously demonstrated BTO-on-Si devices was suffering strongly from large propagation losses in the passive waveguides [9]. Resolving this issue [10] to make BTO waveguides with less than 3 dB/cm loss has allowed us to explore the full potential of BTO photonic devices. Combined with a record Pockels effect of >900 pm/V [11], we have demonstrated various types of BTO-Si modulators, switches, and tuning elements [8], [11]–[13].

Using Mach-Zehnder modulators fabricated on a silicon substrate (Fig. 2b) we have demonstrated excellent $V_\pi L$ values of just 0.2 Vcm (Fig. 2c), one order of magnitude lower than typical silicon-based modulators [14]. Because of the low propagation losses in BTO-Si waveguides, the same devices can also be used for efficient low-loss tuning and switching with a $P_\pi$ on the order of 100 nW [8], [13], while silicon thermo-optic tuning typically requires 100's of µW [15].

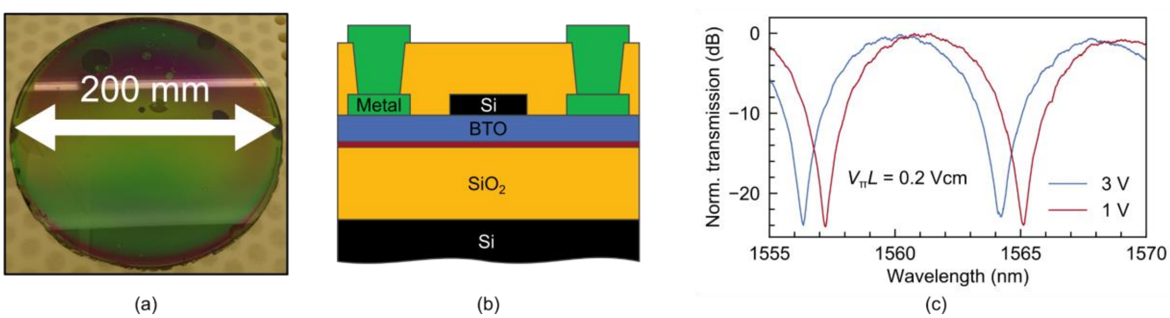


Fig. 2. (a) Wafer bonding of BTO layers using 200mm substrate wafers. (b) Schematic cross-section of the BTO devices fabricated on silicon substrates. (c) Tuning of BTO Mach-Zehnder modulator showing a $V_\pi L$ of just 0.2 Vcm.

While the bandwidth of the monolithically integrated Mach-Zehnder modulators was limited by RF design, we have demonstrated low-Q ring modulators with a bandwidth of 30 GHz (Fig. 2b). Using rings with a radius of 12.5 µm we have were able to record eye diagrams at 20 Gbps using a source voltage of just 1 V to drive the modulator (Fig. 2c). To reach the ultimate limit in terms of operating speed, we have also explored plasmonic BTO modulators that work at data rates beyond 50 Gbps, as discussed in [11], [12].

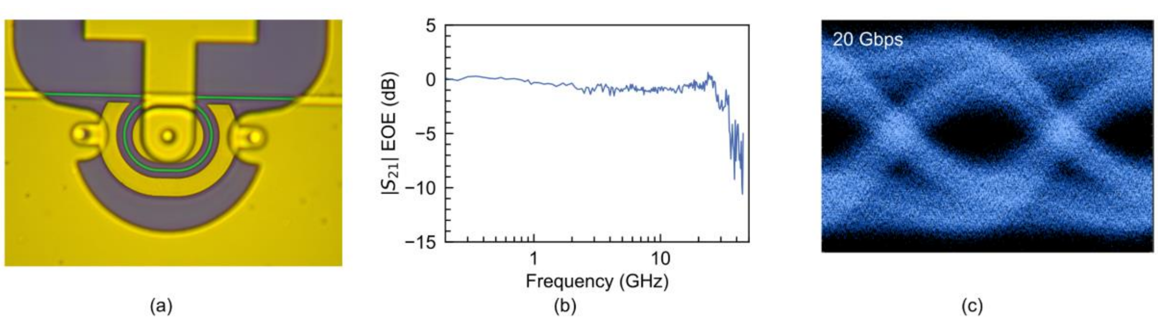


Fig. 3. (a) BTO-Si ring modulator. (b) Bandwidth measured in low-Q ring modulator. (c) Eye diagrams of modulated signal from ring modulator. Data was transmitted at 20 Gbps using a source voltage of 1 V to drive the modulator.

## 4. Summary

We have combined BTO with conventional silicon photonic platforms to enhance the performance of silicon photonics by exploiting the Pockels effect. We have demonstrated modulators, switches, and tuning elements with excellent performance exceeding that of silicon-based devices. The efficiency, low losses, and low static power of BTO-Si devices results in a significant improvement in power consumption of silicon photonics technology. Bringing the Pockels effect to an integrated photonics platform also has implication beyond convention applications in fields such as neuromorphic and quantum computing [16], [17].

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## References

[1] G. T. Reed, G. Mashanovich, F. Y. Gardes, and D. J. Thomson, "Silicon optical modulators," *Nat. Photonics*, vol. 4, pp. 518–526, 2010.
[2] A. H. Atabaki, A. A. Eftekhar, S. Yegnanarayanan, and A. Adibi, "Sub-100-nanosecond thermal reconfiguration of silicon photonic devices," *Opt. Express*, vol. 21, no. 13, pp. 15706–15718, 2013.
[3] C. Kieninger *et al.*, "Ultra-high electro-optic activity demonstrated in a silicon-organic hybrid modulator," *Optica*, vol. 5, pp. 1–5, 2018.
[4] K. Alexander *et al.*, "Nanophotonic Pockels modulators on a silicon nitride platform," *Nat. Commun.*, vol. 9, p. 3444, 2018.
[5] C. Wang *et al.*, "Integrated lithium niobate electro-optic modulators operating at CMOS-compatible voltages," *Nature*, vol. 562, pp. 101–104, 2018.
[6] R. a. McKee, F. J. Walker, J. R. Conner, E. D. Specht, and D. E. Zelmon, "Molecular beam epitaxy growth of epitaxial barium silicide, barium oxide, and barium titanate on silicon," *Appl. Phys. Lett.*, vol. 59, no. 7, pp. 782–784, 1991.
[7] N. Daix *et al.*, "Towards large size substrates for III-V co-integration made by direct wafer bonding on Si," *APL Mater.*, vol. 2, no. 8, p. 086104, 2014.
[8] F. Eltes *et al.*, "A BaTiO3-based electro-optic Pockels modulator monolithically integrated on an advanced silicon photonics platform," *J. Light. Technol.*, vol. 37, no. 5, pp. 1456–1462, 2019.
[9] C. Xiong *et al.*, "Active silicon integrated nanophotonics : ferroelectric BaTiO3 devices," *Nano Lett.*, vol. 14, no. 3, pp. 1419–1425, 2014.
[10] F. Eltes *et al.*, "Low-loss BaTiO3-Si waveguides for nonlinear integrated photonics," *ACS Photonics*, vol. 3, no. 9, pp. 1698–1703, 2016.
[11] S. Abel *et al.*, "Large Pockels effect in micro- and nanostructured barium titanate integrated on silicon," *Nat. Mater.*, vol. 18, no. 1, pp. 42–47, 2019.
[12] A. Messner *et al.*, "Plasmonic Ferroelectric Modulators," *J. Light. Technol.*, vol. 37, no. 2, pp. 281–290, 2019.
[13] J. E. Ortmann *et al.*, "Ultra-Low-Power Tuning in Hybrid Barium Titanate–Silicon Nitride Electro-optic Devices on Silicon," *ACS Photonics*, Oct. 2019.
[14] D. Patel *et al.*, "Design, analysis, and transmission system performance of a 41 GHz silicon photonic modulator," *Opt. Express*, vol. 23, no. 11, pp. 14263–14287, 2015.
[15] S. Chung, M. Nakai, and H. Hashemi, "Low-power thermo-optic silicon modulator for large-scale photonic integrated systems," *Opt. Express*, vol. 27, no. 9, pp. 13430–13459, 2019.
[16] S. Abel, D. J. Stark, F. Eltes, J. E. Ortmann, D. Caimi, and J. Fompeyrine, "Multi-Level Optical Weights in Integrated Circuits," in *2017 IEEE International Conference on Rebooting Computing (ICRC)*, 2017.
[17] F. Eltes *et al.*, "An integrated cryogenic optical modulator," *arXiv:1904.10902*, 2019.