Barium titanate emerges as a route to faster AI optical links

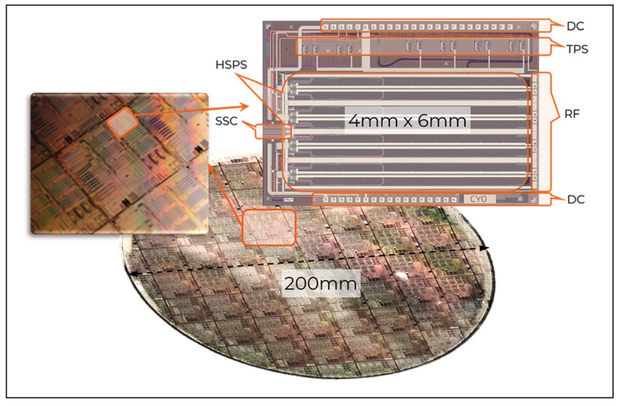


A barium titanate modulator built on a commercial silicon photonics line has carried a record net 1.6 T — and production-grade metal-oxide epitaxy is the quiet enabler that finally makes it manufacturable.

BY DR SABINA HATCH, SALES DIRECTOR, DCA INSTRUMENTS OY

AT THIS YEAR'S Optical Fiber Communication Conference (OFC) in Los Angeles, a post deadline paper delivered a result the silicon photonics community has chased for more than a decade. A four-channel transmitter chip, built on a commercial 200 mm silicon photonics line, pushed a net 1.6 terabits per second — four lanes of 448 Gb/s — through 2 km of standard fibre. Researchers from McGill University in collaboration with Ciena and the Swiss company Lumiphase achieved it not with an exotic laboratory assembly, but with a 5.1 × 3.5 mm² die whose active ingredient is a ferroelectric oxide: barium titanate, or BTO [1].

The same week, the same McGill–Lumiphase partnership reported a companion result: a BTO dual-polarisation IQ modulator carrying a net 1 Tb/s on a single wavelength, both over an 80 km link modelled on the ZR standard and over a 2 km "coherent-lite" link of the kind hyperscalers are eyeing for the inside of the data centre [2].

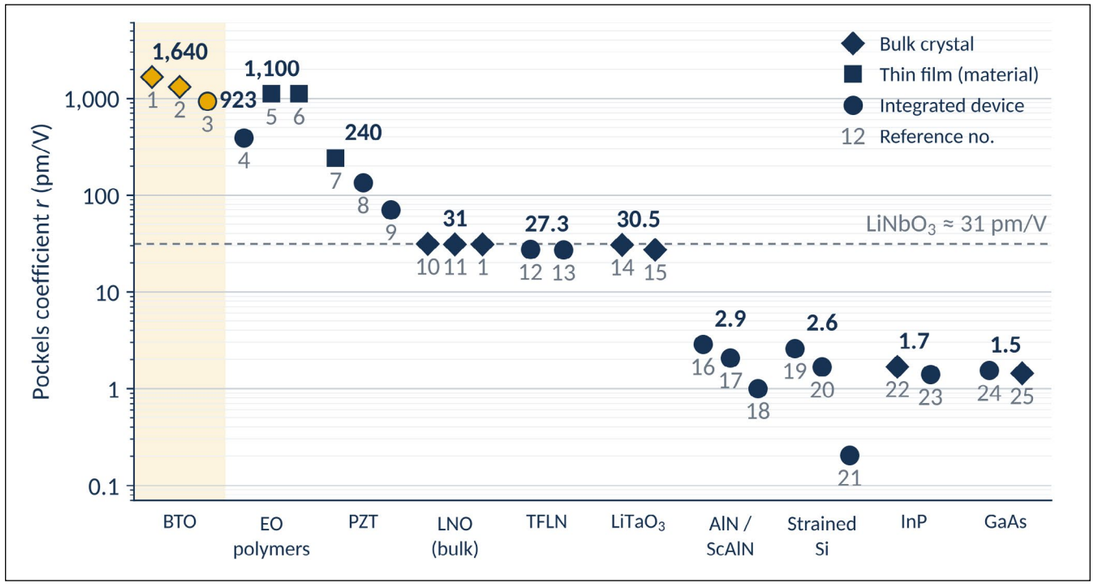


➤ Figure 1: A fully processed 200 mm BTO-on-silicon-photonics wafer, monolithically integrated at wafer level, with a zoom-in of a single reticle and a die shot of a C-band dual-polarisation IQ modulator supporting up to 130 GBd DP-16QAM in a 4 × 6 mm² die.

Why does this matter? Because AI has moved the bottleneck. Every new generation of accelerators multiplies the data that must flow between chips, boards and racks, and the optical links that carry that traffic must deliver more bits at lower energy and in less space with every product cycle. The laser, the fibre and the detector have largely kept pace. The component that has not is the modulator — the device that imprints data onto light. And the reason it has not is a materials problem that silicon photonics has carried since its beginning, roughly fifteen years ago.

Silicon remains an excellent platform for guiding light, and it comes with the full manufacturing weight of the CMOS industry behind it. The catch is its crystal symmetry, which rules out the Pockels effect — the clean, field-driven switching mechanism the best modulators rely on. Without it, silicon modulators have to shuttle charge carriers in and out of the light path instead, and that approach is inherently slower, lossier, and more prone to distortion.

Thin-film lithium niobate (TFLN) brought the Pockels effect back and pushed bandwidth to new records. But its Pockels coefficient is only moderate, so low-voltage devices still end up long. Lithium niobate also can't be grown directly on silicon — it has to be sliced from bulk crystals and bonded onto a wafer, a process most mainstream foundries simply aren't built for. Lithium itself brings contamination risks that make it a poor fit for standard CMOS lines. Indium phosphide modulators are fast, but they're stuck on small, costly 3- to 6-inch wafers.



➤ Figure 2: How the leading electro-optic materials compare. The Pockels coefficient – the strength of the linear electro-optic effect – of thin-film BTO integrated on silicon (≈923 pm/V) is roughly 30 times that of lithium niobate (≈30 pm/V), while strained silicon manages only a marginal effect; bulk BTO crystals exceed 1,000 pm/V. A larger coefficient permits shorter phase shifters, lower drive voltages and lower energy per bit.

What the industry has wanted all along is a material with a huge Pockels effect that can be manufactured on silicon, in a silicon fab. Barium titanate is that material — and the OFC results suggest its moment has arrived, in two markets at once: the terabit interconnects of AI data centres, and the fast, low-loss optical switches of photonic quantum computers.

Why barium titanate wins

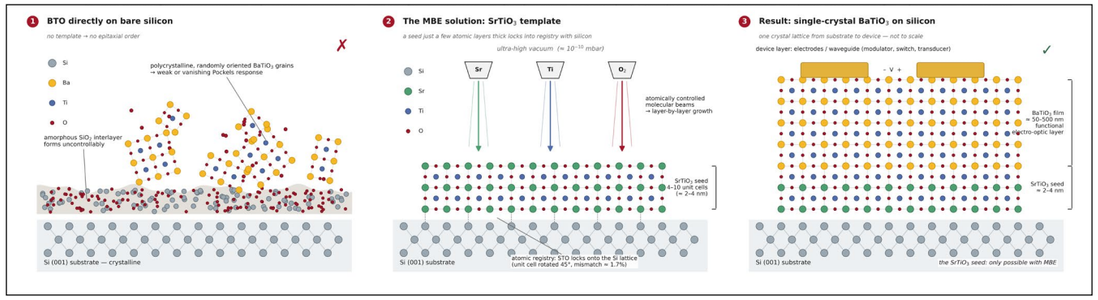
The Pockels effect is easiest to picture as a material whose refractive index — the "stiffness" it presents to light — shifts instantly in response to an electric field. Apply a voltage and the light travelling through speeds up or slows down by a whisker; remove it and the material relaxes, essentially instantaneously. Nothing physical has to move and no charge has to be injected or swept out, so the effect is fast, linear and adds almost no optical loss.

How strongly a material's refractive index shifts is captured by its Pockels coefficient, and this is where BTO is extraordinary. In 2019, a team led by IBM Research in Zurich measured a coefficient of roughly 923 pm/V in thin BTO films integrated on silicon [3] about thirty times that of lithium niobate — and demonstrated data modulation at 50 Gb/s. In bulk crystals the coefficient exceeds 1,000 pm/V, among the largest of any known oxide. A larger coefficient is not an academic nicety: it means the same optical phase shift can be achieved with a shorter electrode, a lower voltage, or both. Shorter means more channels per die; lower voltage means fewer joules per bit. For interconnects whose power budget is now the limiting line item in AI infrastructure, that trade is the whole game.

A fair-minded reader will ask about the fine print, because there is some. In 2025, researchers at ETH Zurich measured BTO and lithium niobate continuously from 100 MHz to 330 GHz and confirmed that BTO's Pockels coefficient, unlike lithium niobate's, falls with frequency [4]. Crucially, the same study showed that BTO remains a remarkable electro-optic material across the entire range, and that devices can be engineered for a flat frequency response despite the dispersion. The OFC hardware is the proof: the Lumiphase-built modulator in the 1.6 Tb/s demonstration shows a 6 dB electro-optic bandwidth of 105 GHz — well clear of any previous non-plasmonic BTO device — and maintained its performance at 85 °C, the kind of case temperature a pluggable module actually experiences, with only a marginal penalty attributed to the electronics. Thin-film BTO devices have even demonstrated penalty-free operation up to 250 °C [5], far above the 120 °C Curie point of the bulk crystal.

The hard part: growing a crystal that does not want to grow

If BTO is so good, why has it taken this long? Because the material is brutally difficult to make well. The Pockels effect lives in the perfection of the crystal: BTO must be deposited as an ordered, single-crystal-like film with the right atomic



➤ Figure 3: Why molecular beam epitaxy is indispensable. BTO will not grow as an ordered crystal on bare silicon; a strontium titanate (STO) seed layer, just a few atomic layers thick and grown by MBE in ultra-high vacuum, locks into registry with the silicon and presents the perovskite template on which crystalline BTO can then form. The schematic shows the layer sequence from silicon substrate to functional BTO device film.

arrangement, the right oxygen content, and clean interfaces. Deposited onto bare silicon, it simply will not comply — the atomic spacings and surface chemistry are wrong, and the film grows disordered, with its electro-optic strength largely lost.

The solution, established in the IBM-lineage research that underpins today's devices, is a seed layer. A film of strontium titanate (STO), only a few atomic layers thick, is first grown on the silicon surface. STO bridges the structural gap: it locks into registry with the silicon beneath while presenting a perovskite template above, onto which BTO then grows as a well-ordered crystal.

That seed layer is the crux of the whole supply chain because there is essentially one way to make it: molecular beam epitaxy (MBE). MBE assembles films in ultra-high vacuum, atom by atom, with independent control over each element's flux and over the oxygen environment — gentle and precise enough to coax a crystalline oxide onto silicon without oxidising the interface into useless amorphous glass. Faster deposition methods cannot match this feat. Sputtering, for instance, is a workhorse of the semiconductor industry and attractive for throughput, but it cannot nucleate the ordered STO template on bare silicon; where sputtering is used for the BTO layer itself, it relies on an epitaxially seeded template underneath. No MBE-grown seed, no crystalline BTO on silicon — it is as close to a hard dependency as materials science offers.



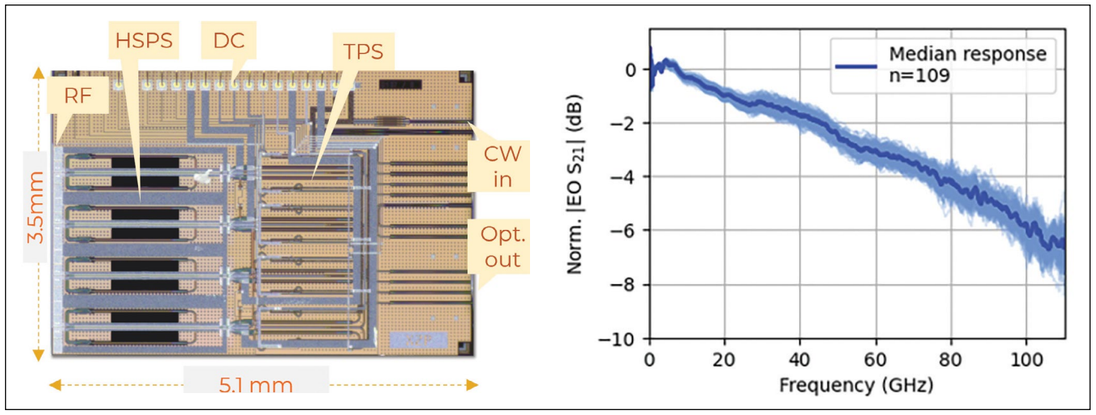
➤ Figure 4: Production metal-oxide MBE: DCA's M-series platform supports wafers up to 300 mm with an integrated equipment front-end module (EFEM), fully automated wafer transfer, 24/7 batch processing and closed-loop process feedback – the fab-compatible architecture that carries oxide epitaxy from laboratory to volume manufacturing.

For years that dependency looked like a dead end, because MBE carried a reputation as a delicate research technique: slow, manual, a tool for papers rather than products. That reputation is out of date. DCA Instruments, the Finnish ultra-high-vacuum specialist founded in 1989, has delivered more than 300 systems worldwide and in 2019 built the world's first production metal-oxide MBE for 300 mm wafers — the wafer size on which modern silicon photonics economics depend. Its production platforms pair the physics of MBE with the furniture of a modern fab: an integrated equipment front-end module for standard wafer handling, fully automated transfer and 24/7 batch processing, ultra-low-particle operation, and closed-loop process feedback. Production statistics presented by DCA at PIC International 2026 — three-sigma uniformity figures across 100-wafer runs of solid-source MBE-grown BTO — show what that translates to on the factory floor. And for the throughput question that always follows, a hybrid-MBE route that delivers titanium from a metal-organic precursor is raising growth rates, with reported device performance so far comparable to the all-solid-source process [6].

The pattern is familiar from other corners of the industry: a once-exotic technique matures into production infrastructure, and a material follows it out of the laboratory. EUV lithography needed its light source; BTO-on-silicon needed production-grade oxide MBE.

What terabit-class modulators buy

Return to the OFC numbers with that context, and their significance sharpens. The 1.6 Tb/s chip is not a hero experiment; it reads like a product preview.



Four Mach-Zehnder modulators with 1.75 mm phase shifters sit beside integrated germanium monitor photodiodes, on-chip terminations, and thermal tuners, in a die small enough for the tightly packed optics of a 1.6T pluggable transceiver. The electrical drive came from a 225 GBaud serialiser/deserialiser fabricated in 3 nm CMOS — exactly the class of silicon that will sit beside these modulators in real modules. All four channels ran 448 Gb/s PAM4 below the hard-decision FEC threshold over 2 km, the first time any silicon photonics platform has carried a net 400 Gb/s lane with PAM4, and pushing the same chip to PAM6 and PAM8 signalling yielded net rates of 2.02 and 2.16 Tb/s.

The coherent result matters for a different reason. As lane rates climb past 200 Gb/s, simple intensity-modulated links strain, and the industry is examining "coherent-lite" architectures — stripped-down coherent links that promise better sensitivity inside the data centre without the full power cost of long-haul signal processing. The BTO dual-polarisation IQ modulator demonstrated a net 1 Tb/s per wavelength in both an 80 km ZR-style system and a 2 km coherent-lite system, with a packaged half-wave voltage of just 0.4 V at 1 GHz. A detail worth savouring: on the coherent prototype, the operating points are held not by miniature heaters, as in conventional silicon photonics, but by BTO's own Pockels effect — under 5 mW, against 13 mW per phase shift for the equivalent thermal tuners. It is an option rather than an obligation: later iterations, including the IMDD transmitter, use silicon thermal tuners where that is the simpler choice. But the arithmetic changes with scale. A transmitter has a handful of phase shifters; an optical switch matrix has thousands, every one of them holding a bias indefinitely. There, static power is the design constraint, and a material that holds its state on a voltage rather than a current stops being a nicety and becomes the reason the switch fabric is buildable at all.

From material to market

Lumiphase, a Swiss company founded in 2020, has pioneered and industrialised the technology: epitaxial BTO grown on silicon by MBE is integrated at wafer scale into a 200 mm commercial silicon photonics flow alongside the silicon, silicon nitride and germanium layers of a standard platform. The OFC devices — the four-channel PAM4 transmitter and the dual-polarisation IQ coherent modulator — are based on epitaxial starting material grown on metal-oxide MBE systems supplied by DCA Instruments.

Lumiphase is not alone, and the breadth of the field is itself evidence that BTO has crossed from curiosity to platform. PsiQuantum, the Palo Alto quantum computing company, published its manufacturable photonic quantum computing platform in Nature in 2025 [7] — built in GlobalFoundries' 300 mm fab — and named BTO electro-optic switches as the key next-generation component for the fast, low-loss photon routing that fault-tolerant photonic quantum computing demands. Its MBE-grown BTO phase shifters achieved a loss–voltage product of 0.33 dB·V, a figure of merit that opens a path to the large switching networks a useful quantum machine will need. That integration work also reported a 95% functional yield for BTO devices in the 300 mm flow — about as strong a manufacturability statement as a new material can earn.

A third player closes the loop on supply. La Luce Cristallina, based in Austin, Texas, sells BTO-on-silicon as a product: in 2025 it opened a wafer fabrication facility — equipped with deposition systems from DCA Instruments — and now offers 200 mm BTO wafers and epitaxial STO-templated substrates to device makers who want the material without building an epitaxy operation of their own. Its route applies RF sputtering to the thicker BTO layer on an epitaxially templated surface, trading some growth finesse for throughput — a sign of a supply chain beginning to differentiate, the way mature materials markets do.

Three companies, three business models — a vertically integrated device maker, a quantum computing developer, and a merchant wafer supplier — on two continents, addressing two very

➤ Figure 5: The record-setting chip. Micrograph of the four-channel BTO/silicon-photonics transmitter die (5.1 × 3.5 mm²) presented at OFC 2026, alongside its measured electro-optic response – a 6 dB bandwidth of 105 GHz. All four channels achieved 448 Gb/s PAM4 below the hard-decision FEC threshold over 2 km, for a net 1.6 Tb/s.

different end markets. What they share is the same enabling step: precision metal-oxide epitaxy, on production-grade tools.

What comes next

The next chapter is about volume. The 200 mm demonstrations are done; the equipment for 300 mm exists; and the customers are explicit about their roadmaps — hyperscalers planning 448 Gb/s lanes and co-packaged optics, and quantum developers whose utility-scale machines call for millions of optical switches apiece. Industry forecasts cited by the wafer suppliers put the optical interconnect market above $34 billion by 2030, and every credible path to those volumes runs through foundry-compatible materials.

Expect three developments. First, BTO modulators will move from post deadline papers into transceiver and co-packaged-optics product programmes, where their short phase shifters and sub-volt drive directly attack the energy-per-bit and bandwidth density targets AI infrastructure now sets. Second, epitaxy throughput will keep climbing — hybrid MBE and sputter-on-template routes are early signs of a maturing toolbox — pulling wafer costs down the same curve every successful semiconductor material has ridden. Third, the quantum and datacom threads will reinforce each other: every yield point learned in a 300 mm photonics flow serves both.

Fifteen years ago, silicon photonics struck a bargain: accept a mediocre modulator in exchange for the world's best manufacturing base. Barium titanate, grown by production metal-oxide MBE, dissolves that bargain. The light, at last, has a material that can keep up with the silicon — and the machines that grow it are already on the fab floor.

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