Introduction to the Implementation of Photonic Components on Wafers

For Communication Engineers: From TFLN Wafers to 6G Integration (2024–2025)

Abstract

The implementation of photonic components on wafers (e.g., TFLN or Si photonics) enables scalable, low-latency systems for 6G networks. **The global strategy focuses in 2025 on the industrialization of thin-film lithium niobate (TFLN) through specialized foundries [7] and the development of scalable photonic quantum computers (LNOI/PhoQuant) [8].** This introduction is based on current literature (2024–2025) and highlights fabrication processes (ion slicing, wafer bonding), preferred techniques (MZI integration), and relevance for signal processing. Practical: Table of methods, outlook on hybrid PICs. Sources: Nature, ScienceDirect, arXiv. **A new optoelectronic chip that integrates terahertz and optical signals is key to millimeter-precise distance measurement and high-performance 6G mobile communications [9].**

Contents

1 Basics: Why Wafer Integration in Communication Engineering?

The fabrication of photonic components on wafers (e.g., thin-film lithium niobate, TFLN) revolutionizes communication engineering: Scalable production of integrated circuits (PICs) for RF signal processing, 6G MIMO, and AI-assisted routing. **The transition to high-volume manufacturing is accelerated by specialized TFLN foundries, such as the QCi Foundry, which will accept the first commercial pilot orders in 2025 [7]. Globally, 2025 (International Year of Quantum Science and Technology) highlights the strategic importance of photonics for competitiveness [6].** Wafer-based processes (e.g., ion slicing + bonding) enable monolithic integration of > 1000 components/wafer, with losses < 1 dB and bandwidths > 100 GHz.

Important Note: The technology is hybrid-analog: Optical waveguides for continuous processing, combined with electronic control. This reduces latency (ps range) and energy (pJ/bit), essential for real-time 6G applications.

Current trends (2025): Transition to 300 mm wafers for industrial scaling, focused on flexible, cost-effective processes [1].

2 Realization: Key Processes for Component Integration

The implementation occurs in multi-stage processes, strongly aligned with semiconductor fabrication (e.g., CMOS-compatible). Core steps:

- **Ion Slicing and Wafer Bonding**: For thin films (e.g., $LiTaO_3$ on Si); enables high density without substrate losses [2].
- **Etching and Lithography**: Mask-CMP for waveguide microstructures; precise structures (< 100 nm) for MZI arrays [4].
- **Monolithic Integration**: Co-packaging of electronics/photonics; reduces latency in hybrid systems [5].
- **Flexible Wafer Scaling**: Mechanically flexible 300 mm platforms for cost-effective production [1].

Example: Wafer bonding for LNOI (Lithium Niobate on Insulator): Thickness $t = 525\,\mu\text{m}$, implantation dose $D = 5 \times 10^{16}\,\text{cm}^{-2}$, resulting layer thickness $h \approx 400\,\text{nm}$.

3 Preferred Components and Operations on Wafers

Photonic wafers are suited for linear, frequency-dependent components; analog integration prioritizes interference-based operations for 6G signals. **In addition to TFLN, the silicon nitride (SiN) platform is being promoted to offer PICs for biosciences and sensing [10].**

Preferred: Linear operations (e.g., matrix-vector multiplication via MZI meshes) for AI-assisted routing; non-linear (e.g., logic gates) requires hybrids.

Component	Realization Process	Relevance for Communication Engineering
Mach-Zehnder Interferometer (MZI)	Ion slicing + lithography on TFLN wafers	Phase modulation for demodulation (6G, latency $< 1\,\mathrm{ps}$) [2]
Waveguide Arrays	Wafer bonding (LNOI) + etching	Parallel RF filtering ($> 100\,\mathrm{GHz}$ bandwidth) [3]
Optoelectronic THz Processor	**Si photonics/InP hybrid PICs**	**6G transceivers, millimeter-precise distance measurement [9]**
Quantum Dot Integrator (InAs)	Monolithic Si integration	Hybrid signal amplification for optical networks [5]
Meta-Optics Structures	CMP mask etching on $LiNbO_3$	Gradient filters for BSS in MIMO systems [4]
LNOI Qubit Structures	**Semiconductor fabrication (PhoQuant)**	**Scalable, room-temperature stable quantum computers [8]**
Flexible PICs	300 mm wafers with mechanical flexibility	Mobile 6G edge devices (roll-to-roll fab) [1]

Table 1: Preferred Components: Implementation on Wafers and Applications

4 Literature Review: Latest Documents (2024–2025)

Selected sources on wafer implementation (focused on photonic components; links to PDFs/abstracts):

- **TFLN Foundries and Industrialization:** The **QCi Foundry** (specialized in TFLN) will accept the first pilot orders for commercial production of photonic chips in 2025, marking the industrialization of the platform [7].
- **Mechanically-flexible wafer-scale integrated-photonics fabrication (2024)**: First 300 mm platform for flexible PICs; process: bonding + etching. Relevance: Scalable RF chips for mobile networks. [1]
- **Lithium tantalate photonic integrated circuits for volume manufacturing (2024)**: Ion slicing + bonding for $LiTaO_3$ wafers; density > 1000 components/wafer. Relevance: Low losses for 6G transceivers. [2]
- **LNOI for Quantum Computers (PhoQuant):** Fraunhofer IOF is developing a photonic quantum computer based on **LNOI**, where fabrication methods stem from semiconductor manufacturing and are immediately scalable. This demonstrates the deployability of the LNOI platform for highly complex quantum architectures [8].
- **Fabrication of heterogeneous LNOI photonics wafers (2023/2024 Update)**: Room-temperature bonding for LNOI; precise waveguides. Relevance: Hybrid optoelectronics for signal processing. [3]
- **Fabrication of on-chip single-crystal lithium niobate waveguide (2025)**: Mask-CMP etching for TFLN microstructures. Relevance: Real-time filters for broadband communication. [4]
- **The integration of microelectronic and photonic circuits on a single wafer (2024)**: Monolithic co-integration; applications in optical networks. Relevance: Latency reduction in 6G. [5]

These documents show: Transition to high-volume manufacturing (12,000 wafers/year), with a focus on analog precision for communication engineering.

5 Outlook: Photonic Wafers in 6G Networks

Wafer integration enables cost-effective PICs for base stations: E.g., optical MIMO with < 1 dB loss. Challenges: Increase yield (currently $< 80\%$). Future: AI-assisted fab (e.g., for dynamic routing chips). **The THz chip from EPFL/Harvard demonstrates the enormous potential of optoelectronic integration to process high-frequency radio signals with millimeter precision, opening new application fields in robotics and autonomous vehicles [9].**

References

[1] Mechanically-flexible wafer-scale integrated-photonics fabrication. Nature Scientific Reports, 2024. Link.

[2] Lithium tantalate photonic integrated circuits for volume manufacturing. Nature, 2024. Link.

[3] Fabrication of heterogeneous LNOI photonics wafers. ScienceDirect, 2023. Link.

[4] Fabrication of on-chip single-crystal lithium niobate waveguide. ScienceDirect, 2025. Link.

[5] The integration of microelectronic and photonic circuits on a single wafer. ScienceDirect, 2024. Link.

[6] Leichsenring, H. (2025). Is Quantum Technology at a Turning Point in 2025. The Bank Blog; DPG (2025). 2025 – The Year of Quantum Technologies. LP.PRO - Laser Photonics Technology Forum.

[7] TraderFox (2024). Quantum Computing 2025: The Revolution is Imminent. Markets.

[8] Fraunhofer IOF (2025). Quantum Computer with Photons (PhoQuant). PRESS RELEASE.

[9] Benea-Chelmus, C. et al. (2025). 6G Mobile Communications Are Getting Closer – Revolutionary Chip Enables Optical and Electronic Data Processing. Leadersnet; Nature Communications (Publication).

[10] Fraunhofer HHI (2025). Berlin 6G Conference 2025; Fraunhofer HHI (2025). Photonics West 2025.