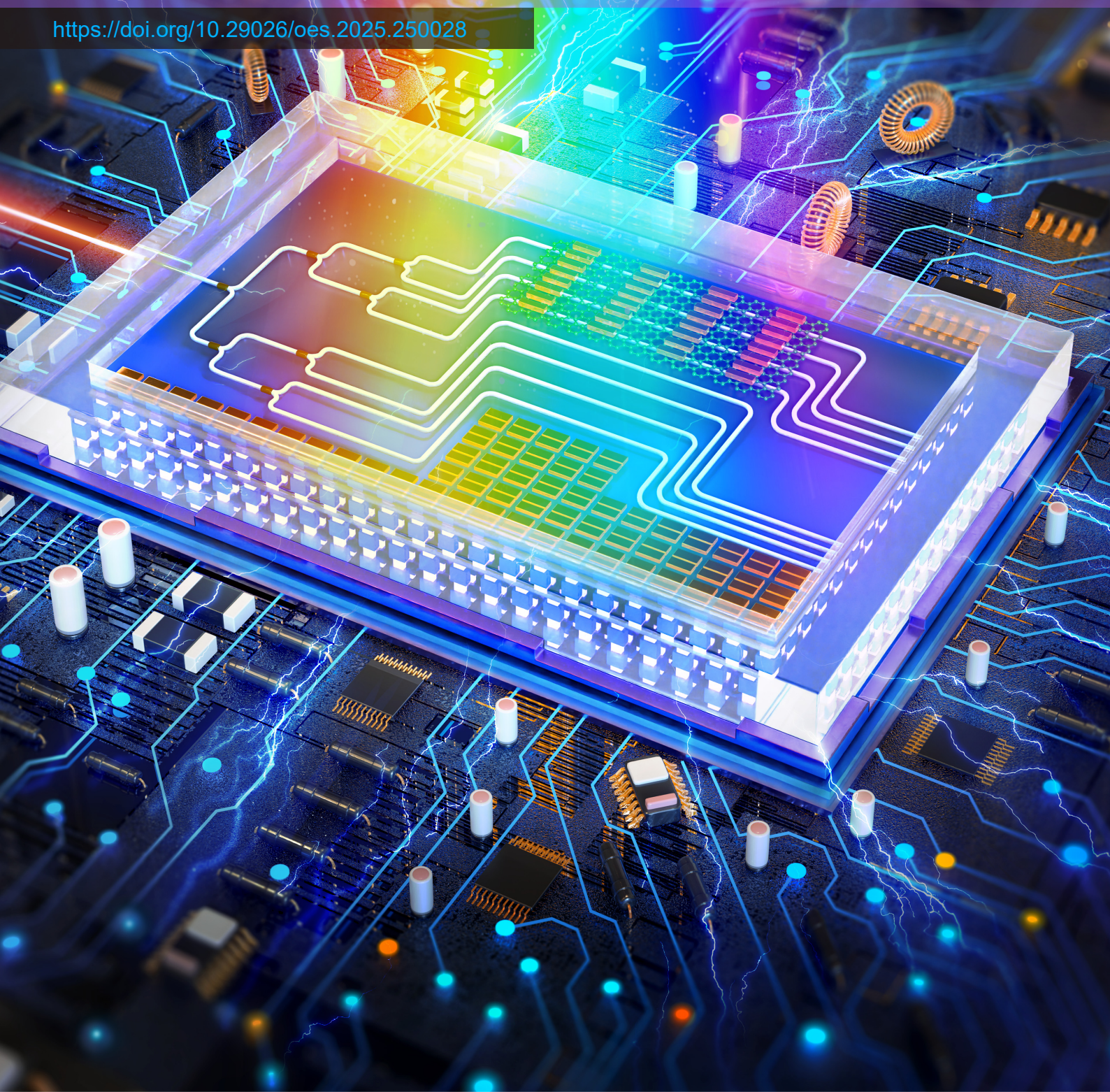


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<https://doi.org/10.29026/oes.2025.250028>



Opto-Electronic Science

CN 51-1800/O4 ISSN 2097-0382 (Print) ISSN 2097-4000 (Online)

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Citation: Sun XL, Jia YC, Chen F. Thin-film lithium niobate-based detector: recent advances and perspectives. *Opto-Electron Sci* 4, 250028 (2025).

<https://doi.org/10.29026/oes.2025.250028>

Received: 7 July 2025; Accepted: 26 September 2025; Published online: 28 November 2025

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Thin-film lithium niobate-based detector: recent advances and perspectives

Xiaoli Sun*, Yuechen Jia^{ORCID} and Feng Chen^{ORCID}*

Thin-film lithium niobate (TFLN) has emerged as a powerful platform for integrated photonics, offering outstanding electro-optic, nonlinear optical, and ferroelectric properties. These unique material characteristics have opened new opportunities for developing high-performance photodetectors with broad spectral response, high sensitivity, and compact integration. This review provides a comprehensive overview of recent progress in TFLN-based detectors, focusing on the underlying physical mechanisms and diverse device architectures. We first discuss the spontaneous polarization, bulk photovoltaic effect, and pyroelectric effect and frequency up-conversion in lithium niobate, which enable unconventional light-to-electricity conversion without external bias. Then, we introduce heterogeneously integrated photodetectors that combine TFLN with III-V semiconductors, silicon, and two-dimensional materials, under both free-space illumination and waveguide coupling configurations. We further highlight advances in integrating single-photon detectors on TFLN platforms, a key step toward scalable quantum photonic systems. In addition, we discuss the direct modification strategies such as ferroelectric domain engineering, doping, and ion implantation modification to enhance the photodetection performance of TFLN devices. Finally, we summarize the existing challenges and present perspectives on the future development of multifunctional, low-power, and quantum-compatible photodetectors based on the TFLN platform.

Keywords: thin-film lithium niobate; photodetector; on-chip optoelectronics; heterogeneous integration; waveguide coupling

Sun XL, Jia YC, Chen F. Thin-film lithium niobate-based detector: recent advances and perspectives. *Opto-Electron Sci* **4**, 250028 (2025).

Introduction

Lithium niobate (LiNbO_3 , LN) has long been recognized as one of the most promising materials in photonics due to its exceptional electro-optic, piezoelectric, and nonlinear optical properties¹. These attributes have enabled a wide range of applications, including electro-optic modulators², optical switches³, and nonlinear frequency conversion processes such as second-harmonic generation (SHG) and sum-frequency generation (SFG)^{4,5}. With a broad transparency range spanning from 400 nm to 5 μm and a high electro-optic coefficient, lithium niobate plays a crucial role in advanced optical communication

systems, high-speed modulators, and quantum photonics. However, the full potential of lithium niobate in integrated photonics has been constrained by the limitations of traditional bulk LN waveguides, including low refractive index contrast, weak optical confinement, and large, cumbersome device structures that hinder their integration into compact photonic circuits. The emergence of lithium niobate on insulator (LNOI) technology has revolutionized the field by overcoming these challenges^{6–8}. Through ion-cutting and wafer-bonding techniques, high-quality ultrathin thin-film LN (TFLN) are fabricated on insulating substrates⁹, significantly enhancing both

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Received: 7 July 2025; Accepted: 26 September 2025; Published online: 28 November 2025



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integration density and optical confinement. The LNOI structure, featuring a low-index insulator cladding, provides a high refractive index contrast ($\Delta n > 1.2$), enabling strong light confinement and reducing bending losses in integrated photonic circuits (PICs)⁵. This advancement has facilitated the development of ultra-compact TFLN-based devices^{10–17}, including photodetectors, with significantly improved sensitivity, efficiency, and power consumption. As a result, LNOI technology represents a major leap forward in lithium niobate photonics, paving the way for more compact, efficient, and scalable integrated photonic circuits^{14,18–20}.

Among the various applications of LN, photodetection is particularly critical, especially in optical communication, quantum sensing, and imaging systems. Photodetectors are essential for converting optical signals into electrical signals and achieving high sensitivity, which is crucial for next-generation optical communication systems, high-performance sensing applications, and quantum computing^{21–23}. Intrinsic lithium niobate-based photodetectors operate through mechanisms such as the bulk photovoltaic effect^{24–26}, two-photon absorption²⁷, and the pyroelectric effect^{28,29}. While these mechanisms offer certain advantages, they also present limitations, including low responsivity and narrow bandwidth, which restrict their practical applications in advanced photonic systems. A major challenge in developing high-performance LN-based photodetectors stems from the material's wide bandgap (~ 4 eV), which results in poor light absorption, particularly in the near-infrared (NIR) and mid-infrared (MIR) regions—critical wavelength ranges for optical communication and sensing technologies. Consequently, intrinsic LN photodetectors exhibit sub-optimal performance in these regions. Addressing this limitation has become a key focus of recent research, leading to the exploration of novel strategies for enhancing light-matter interactions in LN-based photodetectors.

To overcome weak light absorption in the NIR and MIR ranges, researchers have proposed various approaches, including material modification and hybrid integration with other photo-sensitive materials³⁰. Techniques such as ion implantation and defect engineering have been explored to tailor the optical and electronic properties of lithium niobate, enhancing its light absorption and improving overall photodetection performance^{31–33}. These methods aim to strengthen light-matter interactions, leading to increased sensitivity and broader bandwidth, thereby overcoming the inherent

performance limitations of conventional LN-based photodetectors. Additionally, there has been growing interest in hybridizing LN with other materials, such as two-dimensional (2D) materials and III-V semiconductors, to further enhance photodetector performance^{30,34–36}. Integrating LN with 2D materials, such as graphene and transition metal dichalcogenides (TMDs), has shown promise in improving photodetection capabilities, as these materials provide strong light absorption, increased sensitivity, and enhanced responsivity. Similarly, combining LN with III-V semiconductors enables the development of high-performance photodetectors with improved responsivity, fast response times, and broader wavelength detection ranges.

This review provides a comprehensive overview of recent advancements in TFLN-based detectors and offers insights into future research directions in this rapidly evolving field, as shown in Fig. 1. We start from the fundamental principles underlying intrinsic LN-based detection mechanisms, including spontaneous polarization, the pyroelectric effect, the photovoltaic effect, and frequency up-conversion. Then, we systematically summarize and discuss the different strategies for the realization of TFLN-based photodetectors with the free-space illumination and waveguide transmission modes. The single-photon detector and pyroelectric detector of the TFLN are also discussed. Finally, we compare the advantages and disadvantages of different strategies and provide a brief outlook for the development and challenges to the TFLN-based photodetector.

Physical mechanisms of lithium niobate

LN is a multifunctional ferroelectric material that exhibits a rich array of physical properties directly stemming from its non-centrosymmetric crystal structure^{48,49}. These intrinsic properties including spontaneous polarization^{28,50}, bulk photovoltaic effect²⁶, and pyroelectric effect²⁸, not only dominates the LN's unique behavior of optical and thermal phenomena, but also decides the physical mechanism for its broad application in optoelectronic and photonic devices. Understanding these physical effects is essential for optimizing the performance of LN-based integrated photodetectors and expanding their functionality across different wavelength regimes. In this section, we detail the fundamental mechanisms and implications of these key properties, with a focus on how they influence light-matter interaction and enable advanced photodetection strategies.

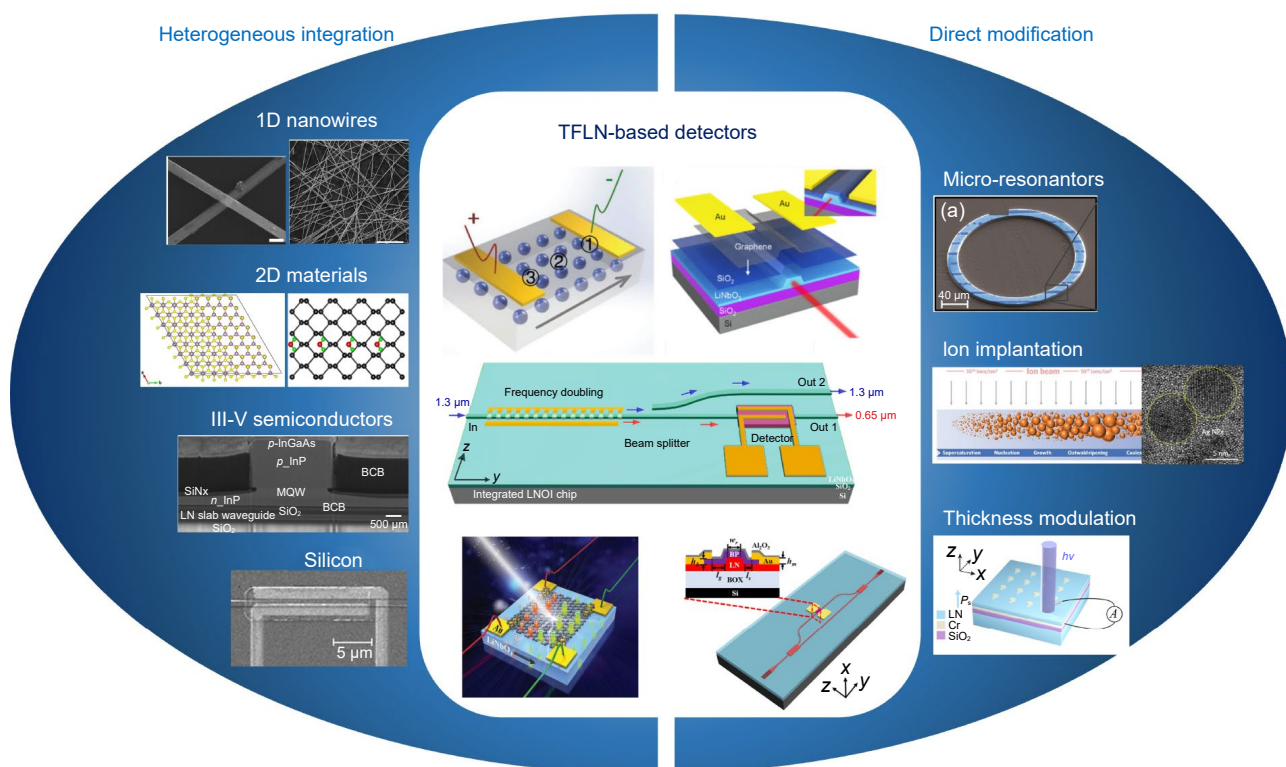


Fig. 1 | Representative strategies for enhancing the performance of TFLN-based photodetectors. Figure reproduced with permission from: ref.³⁷, ref.³⁸, ref.³⁹, Nature; ref.⁴⁰, ACS Publishing; ref.⁴¹, ref.⁴², ref.⁴³ OSA Publishing; ref.⁴⁴, ref.⁴⁵, ref.⁴⁶, ref.⁴⁷, John Wiley and Sons; ref.²⁶, American Physical Society.

Spontaneous polarization

LN crystallizes in a trigonal (rhombohedral) structure with space group $R3c$ at room temperature. The absence of inversion symmetry in this structure results in an asymmetric displacement of lithium (Li^+) and niobium (Nb^{5+}) cations relative to the oxygen (O^{2-}) anions along the polar c -axis, as shown in Fig. 2(a)^{51–54}. This displacement arises from a delicate balance between electrostatic interactions and lattice distortions, generating a stable dipole moment that manifests as macroscopic polarization^{28,50,55,56}. The primary contributors to spontaneous polarization are the Nb^{5+} and Li^+ ion displacements. In the ferroelectric phase, Nb^{5+} is shifted from the center of its oxygen octahedron along the c -axis, inducing an internal electric field. Li^+ ions follow a similar displacement pattern, reinforcing the overall polarization. The spontaneous polarization in bulk LN typically ranges from 60 to 80 $\mu\text{C}/\text{cm}^2$. The ion displacement results in charge separation, leading to the formation of an internal electric field that stabilizes the ferroelectric state and plays a vital role in charge transport and optical interactions. This intrinsic field also influences the electronic band structure, affecting photovoltaic, pyroelectric, and

nonlinear optical properties⁵⁷. Factors such as stoichiometry, doping, and temperature can modulate spontaneous polarization. Defects, including lithium or niobium vacancies, alter local charge distributions and impact polarization strength⁵⁸. Furthermore, doping with elements like magnesium (Mg^{2+}) or zinc (Zn^{2+}) enhances ferroelectric stability while mitigating optical damage^{59–62}. Lithium niobate exhibits a well-defined ferroelectric domain structure, where regions of uniform polarization (domains) are separated by domain walls. These domains can be manipulated through external electric fields, a phenomenon known as ferroelectric domain switching⁶³. When an applied electric field exceeds the coercive field (~ 21 kV/mm), the direction of spontaneous polarization reverses, enabling tunable optical and electronic properties.

The spontaneous polarization has a profound impact on the performance of LN-based photodetectors. First, the built-in electric field enhances carrier separation *via* the photovoltaic effect, reducing recombination of photogenerated electron-hole pairs and increasing quantum efficiency. This effect is particularly beneficial in self-powered photodetectors, enabling high-efficiency

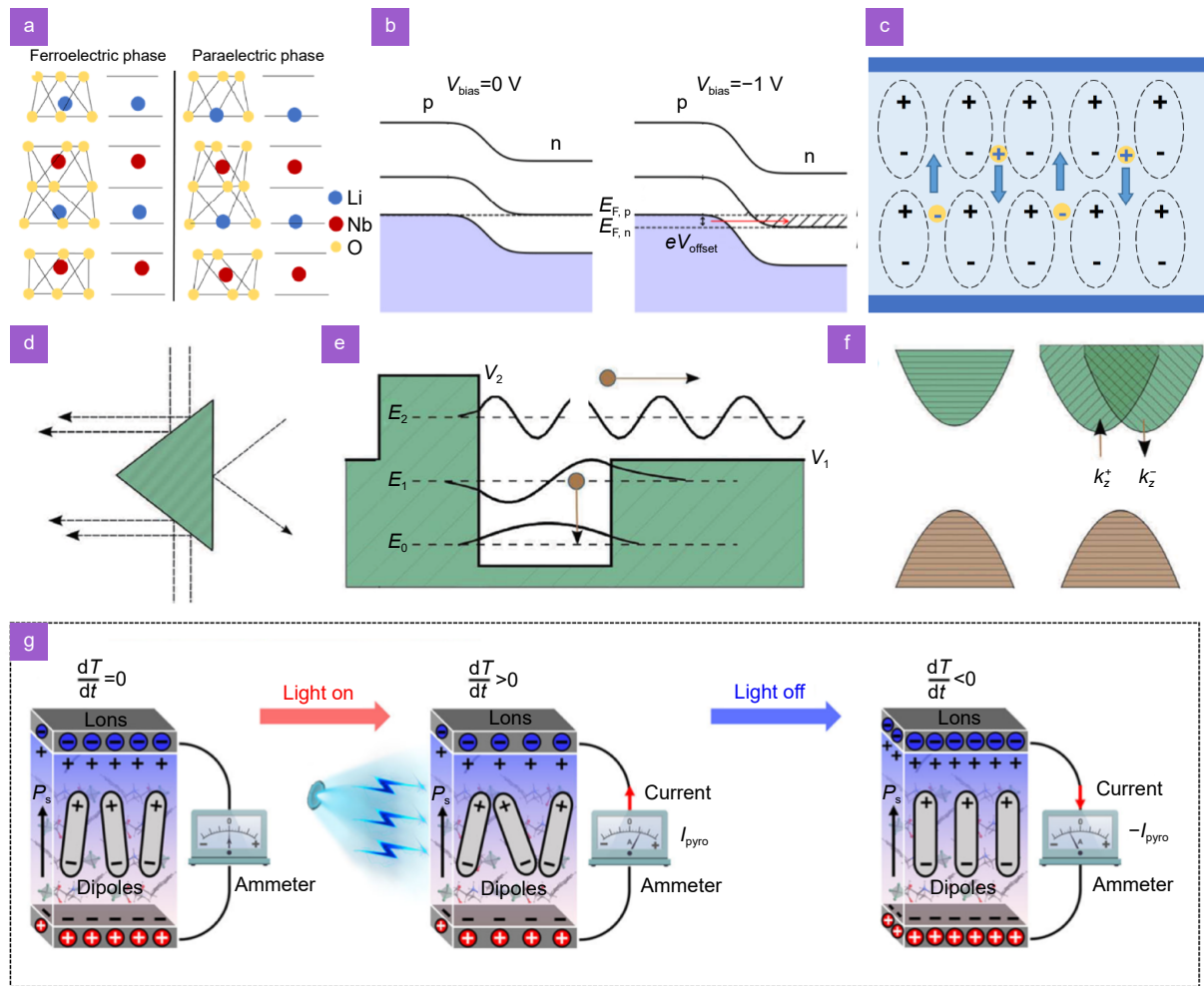


Fig. 2 | Schematic illustrations of intrinsic physical mechanisms in lithium niobate relevant to photodetection. **(a)** Non-centrosymmetric crystal structure of LN, showing displacement of lithium and niobium ions along the polar axis that breaks inversion symmetry and creates a permanent electric dipole moment. **(b)** Internal electric field generated in semiconductor p-n junction. **(c)** The photovoltaic effect in the ferroelectrics. **(d–f)** Representative models for the BPVE: **(d)** Asymmetric scattering centers lead to a net current from randomly moving photocarriers. **(e)** An asymmetric potential well at the photogeneration site causes photocarriers to preferentially escape in a specific direction. **(f)** Relativistic splitting of the conduction band minimum results in distinct excitation pathways; polarized light preferentially excites electrons into one channel, enabling directional current flow. **(g)** Pyroelectric effect in LN: light-induced heating changes temperature rate (dT/dt), altering spontaneous polarization and generating pyroelectric current, with reversed current upon cooling. Dipole orientation, temperature variation, and ionic migration contribute to current generation. Figure reproduced with permission from: (a) ref.⁸², Springer Nature; (b) ref.⁸³, American Chemical Society; (d–f) ref.⁶⁶, Royal Society of Chemistry; (g) ref.⁶⁹, Springer Nature.

photoelectric conversion without an external electric field. Second, the intrinsic pyroelectric effect, which induces polarization charge variations in response to temperature changes, enhances infrared detection. This makes LN photodetectors highly suitable for thermal imaging and infrared applications. By controlling polarization orientation, photodetector responses can be optimized for different wavelengths, facilitating multi-wavelength detection. Furthermore, domain engineering techniques offer additional ways to optimize the photoresponse of LN-based photodetectors. Periodic poling, achieved

through ferroelectric domain switching, enhances non-linear optical interactions and improves signal gain. Ion implantation enables localized modification of polarization, allowing precise control over light-matter interactions to optimize sensitivity and dynamic response⁶⁴. Recent advancements have also explored plasmonic-ferroelectric hybrid structures, where metallic nanoparticles integrated with LN leverage localized surface plasmon resonance (LSPR)⁶⁵. These hybrid structures enhance light localization, improve absorption, and enable wavelength-selective photodetection with superior efficiency.

Bulk photovoltaic effect

The bulk photovoltaic effect (BPVE) in LN is a second-order nonlinear optical process that arises from its non-centrosymmetric crystal structure, enabling photocurrent generation without the need for built-in or externally applied electric fields²⁶. This mechanism is fundamentally distinct from the classical photovoltaic effect observed in p-n junction photodiodes, where charge separation relies on internal electric field gradients across depletion regions, as illustrated in Fig. 2(b). In contrast, BPVE originates intrinsically from the inversion symmetry breaking of the LN lattice, allowing the generation of steady-state photocurrents in homogeneous materials, even under uniform illumination, as shown in Fig. 2(c). The origin of BPVE has been theoretically linked to effects analogous to parity non-conservation in weak interactions, emphasizing its intrinsic symmetry-related nature. Several theoretical models have been proposed to explain the microscopic origin of the BPVE in non-centrosymmetric materials^{25,66}. The earliest theoretical model attempting to explain the bulk photovoltaic effect suggests that antisymmetric scattering centers may exist in ferroelectric materials. The aligned asymmetric scattering centers, such as wedge-shaped defects induced by spontaneous polarization, can produce a net current under illumination. While this mechanism explains current generation *via* asymmetric carrier diffusion, it typically results in localized and transient currents due to entropy constraints, as illustrated in Fig. 2(d)⁶⁷. Another theoretical model is based on the asymmetry of the electrostatic potential. Photoexcited carriers with energies between two potential thresholds experience directional scattering, leading to a net current flow. This effect becomes pronounced in thin films, where the crystal thickness is comparable to the carrier attenuation length. Here, asymmetric momentum distributions of hot carriers under broken inversion symmetry result in real-space displacement during thermalization, as shown in Fig. 2(e)⁵³. The third mechanism involves spin-orbit coupling (SOC), as displayed in Fig. 2(f).

In a non-centrosymmetric medium with short-circuited electrodes under uniform light irradiation, a steady-state photocurrent J_{pv} is generated, whose magnitude depends on the polarization state of the incident light. When the electrodes are disconnected (open-circuit condition), this current leads to the generation of a photovoltage U_{pv} described by²⁵:

$$U_{pv} = \frac{J_{pv}l}{\sigma_d + \sigma_{pv}}, \quad (1)$$

where σ_d is the dark conductivity, σ_{pv} is the photoconductivity, and l is the electrode separation. When $\sigma_d \ll \sigma_{pv}$, which is typical in ferroelectric and piezoelectric materials, the photoinduced electric field E_{pv} becomes:

$$E_{pv} = \frac{J_{pv}}{\sigma_{pv}}, \quad (2)$$

with:

$$\sigma_{pv} = eI_0\alpha\phi(\omega)^{-1}(\mu\tau)_p^v, \quad (3)$$

here, e is the elementary charge, I_0 is the incident light intensity, α is the absorption coefficient, $\phi(\omega)$ is the quantum yield, and μ and τ are the mobility and lifetime of photoexcited carriers, respectively.

In LN, which crystallizes in the $R3c$ space group, the lack of inversion symmetry permits shift currents and injection currents as primary BPVE mechanisms. These occur when photons excite electrons, which then experience asymmetric inter-band transitions. The shift current stems from the coherent displacement of charge centers during excitation, with the resultant carrier motion aligned along the polar c -axis²⁶. This directionality is strongly influenced by the polarization orientation and domain configuration, which can be engineered to optimize current flow. Mathematically, the linear BPVE current can be expressed through the third-rank tensor G_{ijl} as²⁵:

$$J_{pv}^i = \alpha G_{ijl} e^j e^l I_0, \quad (4)$$

where e^j and e^l are components of the light polarization vector. The simplified scalar relations are:

$$J_{pv} = \alpha G I_0, \quad (5)$$

$$E_{pv} = \frac{G\phi(\mu\tau)_{pv}\omega}{e}. \quad (6)$$

One of the most remarkable features of BPVE in LN is its ability to generate open-circuit photovoltages that exceed the bandgap (~ 3.9 eV), suggesting potential for energy harvesting and self-powered detection. However, the efficiency is constrained by the relatively low absorption in the visible and near-infrared due to the wide bandgap. To overcome this limitation, strategies such as defect engineering, doping, and hybridization with narrow bandgap materials (e.g., 2D semiconductors) are employed.

In photodetector applications, BPVE enables self-powered, polarization-sensitive, and ultrafast response functionalities. Devices leveraging this effect benefit

from directional photocurrents that enable spatially resolved imaging and detection, along with reduced thermal noise and broad spectral responsivity. Enhancement strategies include periodically poled domain engineering to modulate the nonlinear response locally⁶³, ion implantation to introduce sub-bandgap states for improved absorption⁴⁵, and heterostructure integration to broaden the spectral response and increase quantum efficiency⁶⁸. Together, these approaches offer a viable path toward realizing high-performance and compact LN-based optoelectronic devices grounded in the unique physics of the bulk photovoltaic effect.

Pyroelectric effect

The pyroelectric effect in ferroelectrics arises from its intrinsic spontaneous polarization, which varies with temperature, as shown in Fig. 2(g)⁶⁹. As a ferroelectric material with strong ionic displacements along the polar *c*-axis, LN exhibits significant temperature-dependent changes in polarization. When the temperature of the material changes, the displacement of Li⁺ and Nb⁵⁺ ions relative to the oxygen framework is altered, resulting in a variation of the spontaneous polarization²⁹. This change in polarization generates a temporary current in external circuitry, known as the pyroelectric current. LN possesses the high pyroelectric coefficients among ferroelectric materials, making it particularly suitable for thermal and infrared detection applications. The pyroelectric coefficient can be defined as the temperature derivative of the spontaneous polarization vector:

$$P_i = \frac{\partial P_{s,i}}{\partial T}, \quad (7)$$

where P_i is the pyroelectric vector and P_s is the spontaneous polarization. Unlike thermal detectors that rely on bolometric principles, pyroelectric detectors based on LN can operate at room temperature and offer rapid response, high sensitivity, and low thermal noise. These features make LN-based photodetectors highly attractive for use in thermal imaging, motion sensing, and far-infrared spectroscopy. The strength of the pyroelectric response in LN can be further optimized through doping, domain engineering, and nanoscale structuring. For instance, magnesium doping (LN:Mg) can suppress photorefractive damage while maintaining or enhancing the pyroelectric response⁶⁰. Periodic poling allows for the creation of domain structures that maximize charge generation upon thermal modulation. Moreover, integra-

tion with plasmonic or photo-sensitive materials (e.g. graphene or metallic nanostructures) can increase infrared absorption, thereby enhancing the temperature-induced polarization change and resulting pyroelectric signal^{70–72}. In integrated photonic systems, the pyroelectric effect in TFLN enables the on-chip thermal sensing. With advances in device design and material engineering, pyroelectric detection in LNOI platforms offers new opportunities for broadband photodetection, environmental monitoring, and thermally tunable optoelectronic components.

Frequency up-conversion

Frequency up-conversion in LN is a nonlinear optical process arising from its large second-order susceptibility ($\chi^{(2)}$)^{73–75}, enabling efficient wavelength conversion through mechanisms such as SHG and SFG. Unlike BPVE and pyroelectric detection, which directly exploit intrinsic ferroelectric and polarization-related phenomena, up-conversion detection relies on nonlinear optical mixing to convert incident photons from longer-wavelength regions, such as the telecom or mid-infrared bands, into shorter wavelengths that can be efficiently detected by mature photodetectors (e.g., Si or InGaAs devices)⁷⁶.

The underlying principle is based on energy and momentum conservation, where the interaction of a signal photon ω_s with a strong pump photon ω_p in the LN lattice produces a higher-frequency photon at $\omega_{uc} = \omega_s + \omega_p$. Efficient realization of this process requires strict phase-matching conditions, which in LN can be achieved through periodic poling (PPLN) or by exploiting modal dispersion in TFLN nanophotonic waveguides^{77,78}. The LNOI platform provides sub-wavelength confinement of optical modes and long interaction lengths, resulting in record-high normalized conversion efficiencies^{79,80}. Importantly, up-conversion preserves the quantum and polarization states of the input signal, enabling faithful translation of both classical and quantum optical information into detectable bands⁸¹. This makes LN a promising candidate for applications in quantum communication, infrared imaging, and multi-band optical receivers. In photodetector applications, TFLN-based up-conversion devices enable indirect detection of photons at otherwise inaccessible wavelengths^{40,76}. For instance, telecom-band photons around 1550 nm can be up-converted into the visible range and subsequently detected by high-performance Si single-photon avalanche diodes

(SPADs), providing low noise, high timing resolution, and compatibility with room-temperature operation⁷⁶. Similarly, mid-infrared photons carrying molecular vibrational information can be frequency-shifted to the near-infrared or visible domain for efficient spectroscopic detection. Unlike conventional mid-IR detectors that require cryogenic cooling, up-conversion detectors based on TFLN operate at room temperature with superior stability and integration potential.

Heterogeneously integrated TFLN photodetector

The heterogeneous integration of LN with other functional materials has emerged as a powerful strategy to overcome the intrinsic limitations of LN, such as its wide bandgap and weak absorption in the visible and NIR regions^{30,84}. This approach enables the development of multifunctional photodetectors that combine the excellent electro-optic, pyroelectric, and ferroelectric properties induced by LN with the strong light absorption and efficient carrier transport capabilities of complementary semiconductors. By integrating LN with materials such as graphene, TMDs (*e.g.*, MoS₂, WS₂), III-V semiconductors (*e.g.*, InGaAs), or narrow-bandgap perovskites, the spectral response of LN-based photodetectors can be significantly extended into the visible and infrared ranges⁸⁵. These hybrid structures capitalize on the broadband absorption and high photoconductivity of the partner materials while benefiting from the unique ferroelectric domain structure, low-loss waveguiding, and high-speed electro-optic modulation.

Hybrid TFLN photodetectors integrated with silicon and III-V semiconductors

Among the various materials used in heterogeneous integration, silicon and III-V semiconductors play particularly crucial roles⁸⁶. Silicon offers mature fabrication processes and excellent compatibility with CMOS platforms^{87,88}, enabling scalable and cost-effective device integration. However, its intrinsic absorption is limited to wavelengths below 1.1 μm , which constrains its standalone detection capability in the infrared. When integrated with LN, silicon-based photodetectors can exploit the electro-optic tunability and waveguiding advantages of LN, resulting in compact, high-speed modulators and detectors suitable for photonic integrated circuits. For example, Marko Lončar and colleagues demonstrated the monolithic integration of a broadband metal-semicon-

ductor-metal (MSM) photodetector for visible light on a LNOI platform⁸⁹.

In addition to silicon, III-V semiconductors such as InGaAs, GaAs, and InP exhibit strong light absorption in the near- and mid-infrared regions. Their integration with LN enables efficient photocarrier generation and amplification, while simultaneously leveraging the domain-engineered nonlinear optical properties and high-speed modulation features⁹⁰. These hybrid devices exhibit enhanced responsivity and extended bandwidth, and can be implemented in both free-space and waveguide-based configurations. In 2022, Marko Lončar's group demonstrated, for the first time, the heterogeneous integration of modified uni-traveling carrier (MUTC) photodiodes on LNOI platform⁹¹, achieving a record bandwidth of 80 GHz and a responsivity of 0.6 A/W at a wavelength of 1550 nm, as illustrated in Fig. 3(a). Lately, Yan et al. reported the integration of InP/InGaAs MUTC photodiodes on a TFLN platform, resulting in an even higher 3 dB bandwidth of 110 GHz and a responsivity of 0.4 A/W at 1550 nm, shown in Fig. 3(b)³⁴. More recently, further optimization of the III-V stack structure led to an improved responsivity of 0.92 A/W at 1560 nm under a bias voltage of -2 V, as shown in Fig. 3(c)⁴¹. These LN-semiconductor hybrid photodetectors offer significant potential for high-speed optical communication, on-chip signal processing, and broadband infrared sensing⁴⁰. Their multifunctionality and integration flexibility make them highly attractive for next-generation optoelectronic systems.

2D materials-TFLN photodetectors

2D materials^{92–94}, such as graphene, TMDs, black phosphorus (BP), and topological insulators, have emerged as promising candidates for heterogeneous integration with TFLN. Owing to their exceptional optical absorption, tunable bandgaps, ultrafast carrier dynamics, and mechanical flexibility, these materials enable high-performance photodetection when combined with the electro-optic, ferroelectric, and pyroelectric properties of TFLN. Two major configurations of 2D materials-TFLN photodetectors have been demonstrated: i) free-space illuminated heterostructures and ii) waveguide-integrated architectures. Each approach leverages distinct light-matter interaction mechanisms and integration advantages.

Free-space illuminations

In free-space illuminated photodetectors based on 2D

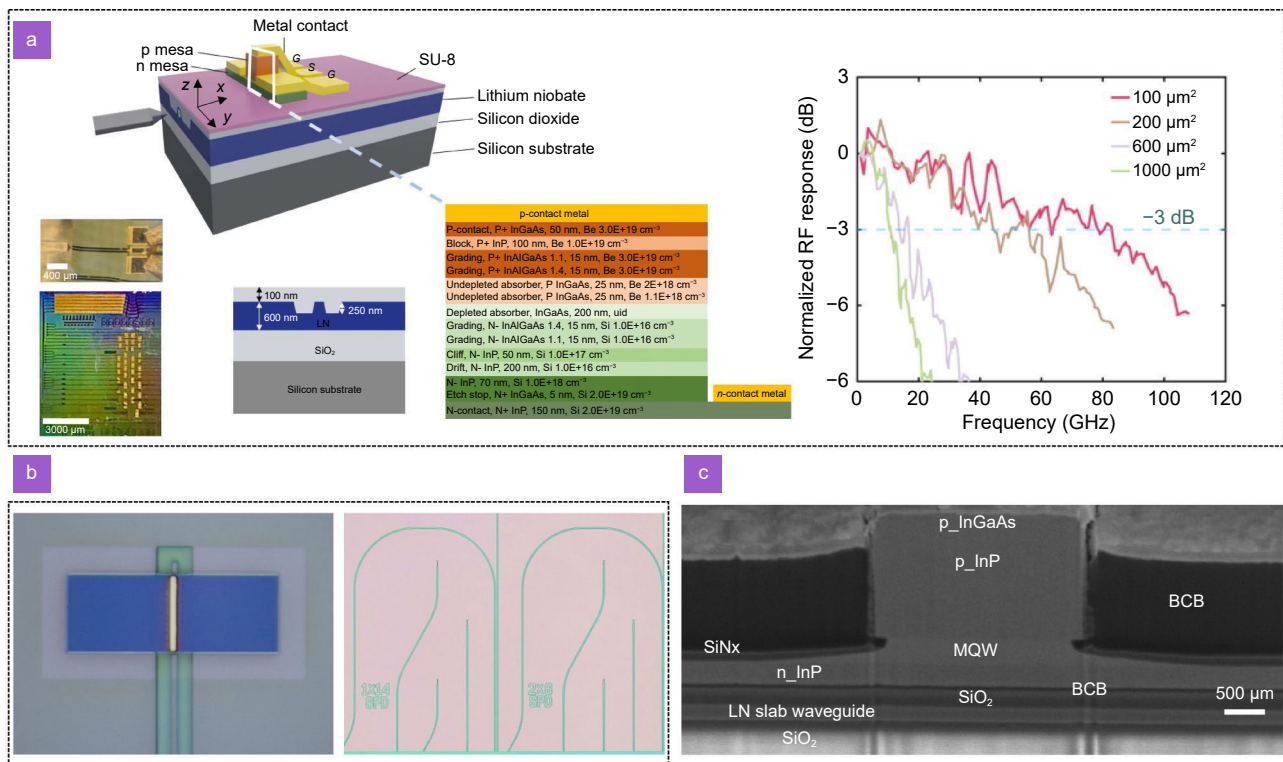


Fig. 3 | Heterogeneously integrated TFLN photodetectors with silicon and III-V semiconductors. **(a)** MUTC photodiodes integrated on TFLN. **(b)** InP/InGaAs MUTC photodiodes heterogeneously integrated on TFLN. **(c)** III-V-on-TFLN integrated photodetector. Figure reproduced with permission from: (a) ref.⁹¹, Chinese Laser Press; (b) ref.⁴¹, Optica Publishing Group; (c) ref.³⁴, under a Creative Commons Attribution License.

materials integrated with TFLN, light from free space is incident perpendicularly onto the device surface, where it directly interacts with the 2D materials such as graphene or TMDs, which is transferred or grown on the TFLN layer. In this architecture, the 2D materials layer functions as the primary photon absorbing medium, while the underlying TFLN substrate serves not only as structural support but also as an active functional platform that modulates the optoelectronic properties of the 2D materials^{95,96}. This modulation arises from several intrinsic physical properties of LN, including spontaneous polarization, pyroelectricity, and the bulk photovoltaic effect. These properties enable precise control over photocarrier generation, separation, and transport within the 2D materials layers, thereby enhancing the device's responsivity, sensitivity, dynamic range, and temporal response⁹⁷.

Among the various modulation mechanisms, the tuning of carrier concentration through spontaneous polarization and the thermal coupling provided by the pyroelectric effect are particularly significant. LN possesses a large spontaneous polarization of approximately 70 $\mu\text{C}/\text{cm}^2$, which generates a strong built-in electric field at

its surface⁵⁵. This intrinsic field is capable of electrostatically doping adjacent 2D materials, effectively modulating their carrier density without the need for an external gate voltage. The direction of the ferroelectric polarization determines the type of doping induced in the 2D materials. When the polarization is oriented toward the 2D materials (referred to as $P \uparrow$ or P^+), it leads to n-type doping^{98–101}. In contrast, when the polarization is directed away from the 2D materials (referred to as $P \downarrow$ or P^-), it results in p-type doping. This polarization-dependent doping behavior was experimentally verified in 2015 by Lane W. Martin et al.⁹⁸. They fabricated graphene/LN heterostructures and observed a transition in doping type that corresponded with the polarization direction. By employing periodically poled z-cut lithium niobate, they successfully formed lateral p-n junctions in graphene, which generated photocurrent under zero external bias. The device exhibited a responsivity of $2 \times 10^{-5} \text{ A/W}$ in the visible spectrum. Similar effects have been reported in devices based on ion-doped graphene and TMDs^{95,97,99,100}. In these systems, the orientation of ferroelectric domains on the lithium niobate surface modifies the Fermi level alignment and influences carrier

transport, leading to enhanced optical absorption performance. As displayed in Fig. 4(a), nonuniform illumination of the substrate causes electron migration away from illuminated regions, creating a nonuniform surface charge distribution⁹⁹. Figure 4(b) illustrates the band structure reconstruction of MoSe₂ induced by domain engineering on the lithium niobate surface¹⁰⁰. Under $P \uparrow$ (P^+) polarization, electron accumulation is dominant in MoSe₂, whereas under $P \downarrow$ (P^-) polarization, hole accumulation becomes dominant. A similar modification in the energy structure is also observed in monolayer WS₂. On the P^+ domain, a negative electrostatic field leads to hole accumulation, which lowers the Fermi level. In contrast, on the P^- domain, a positive electrostatic field results in electron accumulation, shifting the Fermi level upward due to the excess electrons⁹⁶. Recently, Wan et al. systematically compared the photodetection performance of MoS₂ on P^+ and P^- polarized LNOI thin films¹⁰¹. The energy band alignment differs significantly between the two polarization states. Under weak laser illumination (212.2 pW), the P^- state LNOI/MoS₂ photodetector exhibits superior performance, with a maximum responsivity of 113.1 A/W. Very recently, Weng et al. have made a major breakthrough by harnessing the ferroelectric domains of periodically poled LN to achieve in situ, non-volatile doping of monolayer WSe₂ and fabricating a high-quality, precisely aligned p-n homojunction photodetector Fig. 4(c)⁹⁷. At the domain wall, the spontaneous polarization stably modulates the energy bands of WSe₂, resulting in the formation of intrinsic p-type and n-type regions without any external bias or chemical modification. The resulting WSe₂ p-n homojunction exhibits pronounced rectification behavior, with a high on-off ratio of 6.8×10^3 and a responsivity of 0.36 A/W at a wavelength of 450 nm, all under zero-bias conditions. This work not only provides compelling evidence for the robust and reversible control of 2D semiconductor band structures via ferroelectric engineering, but also establishes a new paradigm for the development of scalable, energy-efficient, and high-performance optoelectronic devices.

Compared to z -cut LN, x -cut LN provides enhanced modulation capabilities owing to its inherent in-plane spontaneous polarization¹⁰². Under focused laser irradiation, localized photothermal heating can induce reorientation of ferroelectric domains, resulting in spatially varying surface charge distributions. These variations, in turn, modulate the carrier concentration and band align-

ment in the overlying 2D materials, enabling dynamic and reconfigurable control of its optoelectronic behavior, as illustrated in Fig. 5(a). For instance, Guan and co-workers reported a broadband photodetector based on few-layer graphene transferred onto x -cut TFLN⁴⁶. The device exhibited an exceptionally broad spectral response ranging from 405 nm to 2000 nm, with an ultra-high responsivity of 1.78×10^5 A/W and a fast response time of 3.3 ms. This remarkable performance was closely associated with the interaction between the in-plane spontaneous polarization of x -cut LN and the overlying 2D materials. In particular, the asymmetric pyroelectric charge injection from the x -cut LN surface led to a non-uniform carrier distribution in the TMDs channel, forming an internal n^-/n^+ homojunction, as shown in Fig. 5(b)¹⁰³. Such band structure modulation plays a critical role in enhancing carrier separation and collection efficiency, thereby boosting the overall photoresponse. Moreover, these devices demonstrated strong polarization sensitivity. The photoresponse exhibited strong dependence on the incident angle of linearly polarized light, demonstrating the anisotropic modulation of spontaneous polarization mediated by the pyroelectric effect. This modulation alters the surface-bound charge distribution, thereby affecting the local electrostatic environment of the 2D materials. Polarization-resolved measurements revealed a characteristic "figure-eight" angular dependence of the photocurrent, with polarization ratios reaching 3.87 for WS₂ and 7.42 for MoS₂⁶⁸. Such behavior highlights the device sensitivity to light polarization states. Similar polarization-dependent behavior has also been observed in n-GaN/ x -cut LN devices, where GaN thin films laminated onto ferroelectric LN achieved a high on/off ratio of 10^7 and a peak responsivity of 1.71×10^3 A/W under 325 nm illumination¹⁰⁴. The strong polarization field of x -cut LN effectively separates photo-generated carriers, enabling high-efficiency UV detection with a polarization ratio up to 54.95.

In addition to the role of spontaneous polarization, the pyroelectric effect serves as another critical mechanism influencing the performance of TFLN-based photodetectors²⁹. When the TFLN substrate absorbs optical energy, part of it is converted into heat, leading to a localized temperature rise. This thermal disturbance perturbs the spontaneous polarization via the pyroelectric effect, resulting in the generation of bound surface charges. These charges capacitively couple to the overlying 2D material, inducing free carriers and modulating the local carrier

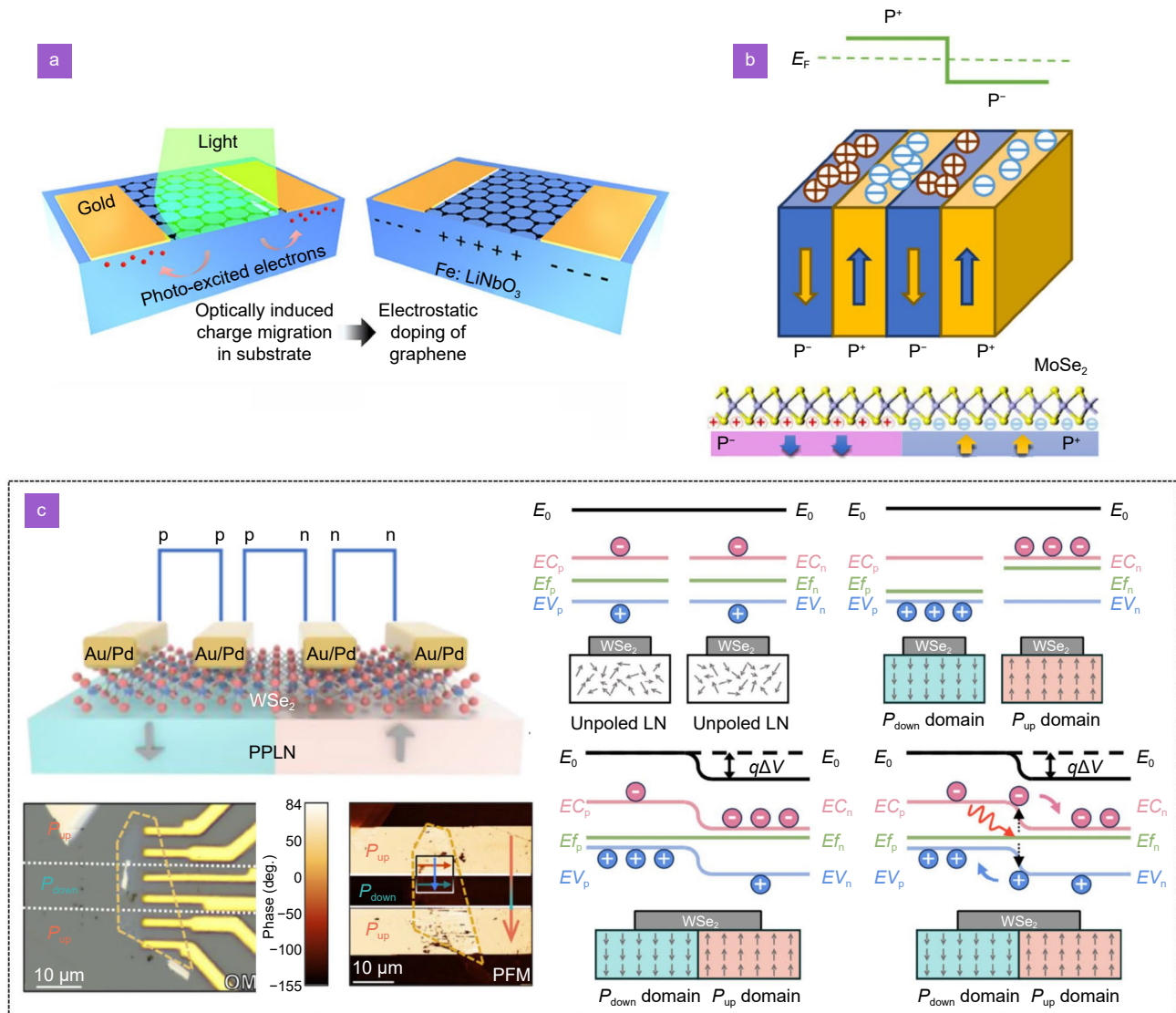


Fig. 4 | Ferroelectric polarization in LN modulating band structure and carrier distribution of 2D materials. (a) Electrostatic environment in graphene/Fe:LN composite under illumination. (b) Surface doping on domain-patterned LN modulating monolayer MoSe₂ band structure: P⁺ surface enriched with positive interface charges enhances electron extraction and suppresses intrinsic n-type behavior. (c) Monolayer WSe₂ pn homojunction photodetector based on PPLN ferroelectric substrate. Figure reproduced with permission from: (a) ref.⁹⁹, (b) ref.¹⁰⁰, American Chemical Society; (c) ref.⁹⁷, John Wiley and Sons.

concentration. This process results in the pyroresistive effect, where the resistance of the 2D materials, particularly graphene, is modulated by thermally induced redistribution of surface charges rather than by direct generation of photocarriers^{29,71,72}. This represents a novel hybrid detection approach that merges aspects of both pyroelectric and bolometric sensing. Unlike conventional pyroelectric detectors that operate based on transient displacement currents, pyroresistive devices function through conductivity modulation, providing a favorable balance between sensitivity, speed, and integration flexibility. Additionally, *x*-cut TFLN devices exhibit a distinc-

tive phenomenon: a transient enhancement of polarization immediately following the abrupt cessation of laser illumination. The rapid thermal relaxation of the lattice momentarily reinforces the internal electric field, thereby improving carrier confinement and substantially reducing the dark current. This effect is particularly advantageous for applications requiring low noise and high contrast⁶⁸, such as biological imaging, environmental monitoring, and optical communication systems.

All in all, free-space illuminated heterostructures combining 2D materials and TFLN present a versatile and powerful platform for multifunctional optoelectronic

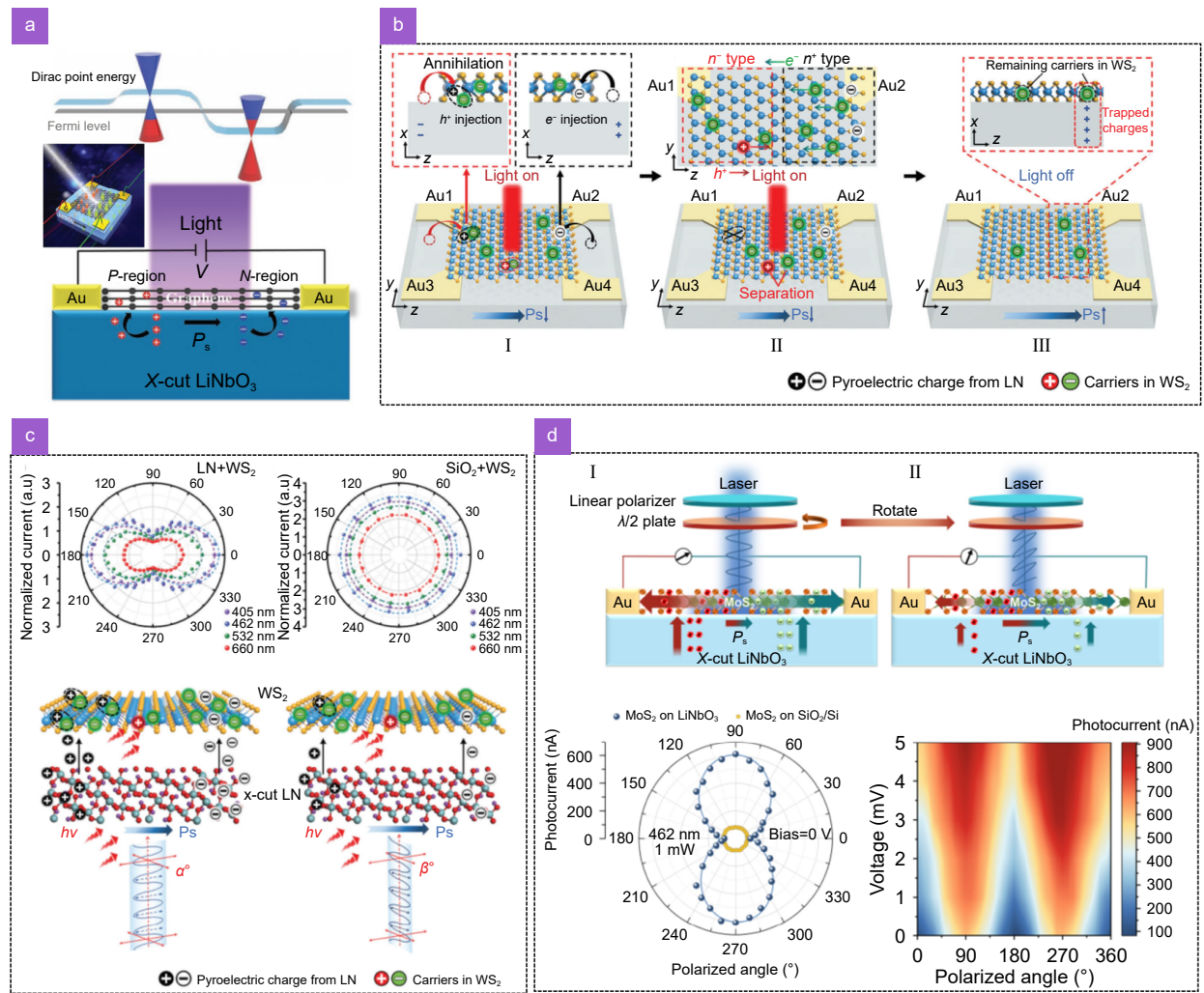


Fig. 5 | Free-space illuminated, heterogeneously integrated TFLN photodetectors incorporating 2D materials. (a) Energy band diagram and device structure of graphene-based TFLN photodetector. (b) Working mechanism of LN/WS₂ heterostructure photodetector. (c) Polarization-sensitive photoresponse comparison between LN/WS₂ and SiO₂/WS₂ photodetectors. (d) Polarization detection behavior of MoS₂ modulated by LN ferroelectric properties. Figure reproduced with permission from: (a) ref.⁴⁶, (b) c) ref.¹⁰³, John Wiley and Sons; (d) ref.⁶⁸, under a Creative Commons Attribution License.

devices. The synergistic effects of ferroelectric polarization, pyroelectric modulation, and the excellent light-matter interaction in 2D materials enable high responsivity, low dark current, broadband spectral sensitivity, and polarization-selective detection in a compact, scalable architecture. These advantages make them highly promising for future integrated photonic and sensing applications.

Waveguide-integrated 2D-TFLN Photodetectors

Waveguide-integrated 2D TFLN photodetectors offer a compact, scalable, and high-performance platform for on-chip light detection^{105,106}. In contrast to free-space illuminated photodetectors, where light impinges perpen-

dicularly onto the surface and the interaction length is limited by the thickness of the active material, waveguide-integrated devices guide light laterally through LN waveguides^{107–109}. In this configuration, the optical mode propagates along the waveguide and interacts with a 2D material placed on the waveguide surface through the evanescent field, as shown in Fig. 6(a)¹⁰⁵. This lateral propagation significantly enhances light-matter interaction by extending the interaction length and confining the optical field within the waveguide structure, leading to much higher absorption efficiency. Additionally, the waveguide geometry is inherently compatible with photonic integrated circuits, allowing for the construction of multifunctional and reconfigurable on-chip photonic

systems¹¹⁰. Experimental studies have shown that waveguide-integrated detectors can achieve responsivity levels up to 160 times higher than those of free-space illuminated counterparts, highlighting their superior performance, as shown in Fig. 6(b)¹⁰⁵. A typical device consists of a ridge or rib waveguide fabricated on a TFLN substrate, on top of which a few-layered 2D materials such as graphene, MoS₂, BP, or molybdenum ditelluride (MoTe₂) is deposited. The evanescent field leaking from the guided mode penetrates the 2D materials layers, enabling efficient photon absorption and carrier generation¹¹¹. By selecting 2D materials with suitable bandgaps and optical absorption characteristics, the spectral response of the device can be tuned from the visible to the mid-infrared range.

Among various 2D materials, the 2H phase of MoTe₂ is particularly appealing for near-infrared photodetection due to its narrow bandgap of approximately 1.0 eV, high carrier mobility, and excellent environmental stability^{112,113}. Xiang et al. integrated MoTe₂ flakes with a thickness of approximately 11 nm onto TFLN ridge waveguides fabricated *via* the proton exchange method, as shown in Fig. 6(c)¹¹⁴. They observed that increasing the waveguide width led to a moderate decrease in MoTe₂ absorption, likely caused by a reduction in evanescent field overlap with the 2D layer. Figure 6(d) displayed the electric field distribution of the fundamental transverse electric (TE₀) mode in the waveguide. Despite this, the device demonstrated low dark current, high responsivity (20.3 mA/W at 1310 nm and 0.23 mA/W at 1550 nm under zero bias), and fast response times of 10.7 μ s and 59.3 μ s, respectively. Increasing the flake thickness to 17 nm further enhanced light-matter interaction, improving the self-powered responsivity to 70 mA/W at 1310 nm, though the response time increased to 160 μ s, as displayed in Fig. 6(e) and 6(f)¹⁰⁶. These findings underscore the importance of optimizing device geometry and material parameters to balance responsivity, speed, and energy efficiency. In a more advanced configuration, Cheng et al. integrated a high-quality factor microring resonator with a MoTe₂ TFLN waveguide photodetector using femtosecond laser photolithography assisted chemical mechanical etching, as shown in Fig. 6(g)¹⁰⁵. This resonator enhanced light confinement and enabled multiple round-trip interactions with the MoTe₂ layer, significantly increasing absorption efficiency. The resulting device exhibited a high signal-to-noise ratio and could detect optical signals as

weak as 16 μ W.

BP is another promising 2D materials for optical communication wavelengths. Its layer-dependent bandgap, which ranges from about 0.3 eV in the bulk to around 2.0 eV in the monolayer, allows broadband absorption from the visible to the mid-infrared^{115,116}. External electric fields or mechanical strain can further modulate its optical properties, enabling spectral tunability. Additionally, BP exhibits strong in-plane anisotropy due to its puckered crystal structure, which enables polarization-sensitive detection, an advantageous feature for on-chip polarimetric imaging and optical information processing¹¹⁷. With high charge carrier mobility (exceeding 1000 cm² V⁻¹·s⁻¹) and fast response speeds, BP-based photodetectors offer high detectivity at room temperature and gigahertz-level operation. In 2023, Bullock J et al. demonstrated the integration of few-layer BP nanosheets onto ridge waveguides on LNOI platforms, as illustrated in Fig. 7(a)¹¹⁸. In this configuration, laser light is coupled into the LNOI waveguide via a fiber-to-chip grating coupler, and partially absorbed by BP photoconductive layer. The device achieved response time of 100 ns and responsivity of 148 mA/W at 1550 nm under low bias, as illustrated in Fig. 7(b). Building on this foundation, Liu et al. developed a Mach Zehnder interferometer-based detector that incorporated integrated grating couplers for efficient light input and output⁴². The structure of the proposed hybrid BP-TFLN waveguide photodetector is shown in Fig. 7(c). To protect the environmentally sensitive black phosphorus layer, an aluminum oxide passivation layer was deposited via atomic layer deposition. This structure achieved enhanced responsivity up to 2.64 A/W across the 1520 nm to 1580 nm range and a 3 dB bandwidth of 1.97 GHz, demonstrating strong potential for high-speed data communication and real-time monitoring. The results are displayed in Fig. 7(d). Subsequently, Ruan et al. optimized the geometrical parameters of proton-exchanged TFLN waveguides¹¹⁹, further improving the performance of BP-TFLN photodetectors. Their device achieved a responsivity of 147 A/W at 1550 nm, along with enhanced linearity and long-term operational stability. The schematic of the optimized structure is shown in Fig. 7(e), and the simulated electric field distributions for the TE₀₀ and TE₁₀ modes are presented in Fig. 7(f). Figure 7(g) and 7(h) illustrate the photodetector's performance as a function of external bias and incident laser intensity. As the external bias voltage increases, the photocurrent exhibits a linear rise, indicating

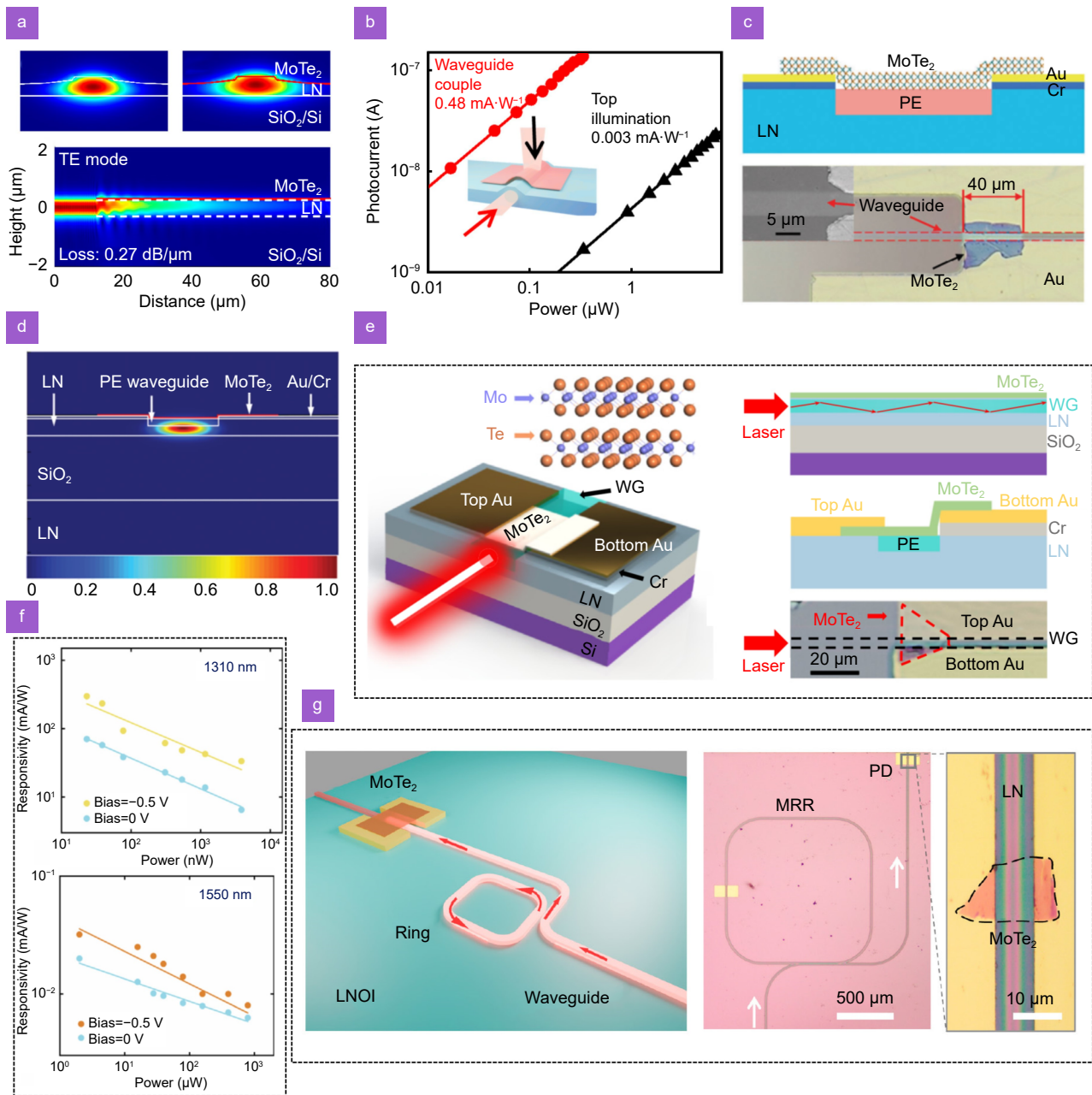


Fig. 6 | Waveguide-coupled, heterogeneously integrated TFLN photodetectors incorporating 2D materials. **(a)** Simulated light field distribution in LNOI waveguide without and with 2D materials. **(b)** Responsivity comparison under waveguide-coupled and spatial illumination. **(c)** Three-dimensional structure and cross-sectional view of MoTe₂ photodetector integrated on PE TFLN waveguide with symmetrical electrodes. **(d)** Electric field distribution of TE₀ mode in PE waveguide. **(e)** Three-dimensional structure and cross-sectional view of MoTe₂ photodetector on PE TFLN waveguide with asymmetrical electrodes. **(f)** Responsivity of photodetectors at varying laser powers under 1310 nm and 1550 nm excitation. **(g)** Schematic of MoTe₂-LNOI photodetector on waveguide-coupled ring resonator; arrows indicate light propagation direction. Figure reproduced with permission from: (a, b, g) ref.¹⁰⁵, MDPI; (c, d) ref.¹¹⁴, John Wiley and Sons; (e, f) ref.¹⁰⁶, Elsevier.

efficient carrier collection under stronger electric fields. In contrast, with increasing incident laser intensity, the photocurrent increases exponentially, while the responsivity decreases exponentially, likely due to saturation effects or increased carrier recombination at higher optical power levels.

While black phosphorus based TFLN detectors demonstrate excellent responsivity, fast response, and broadband coverage, further improvements in stability and photoelectric conversion efficiency are needed. A promising approach is to construct van der Waals heterostructures by integrating black phosphorus with other

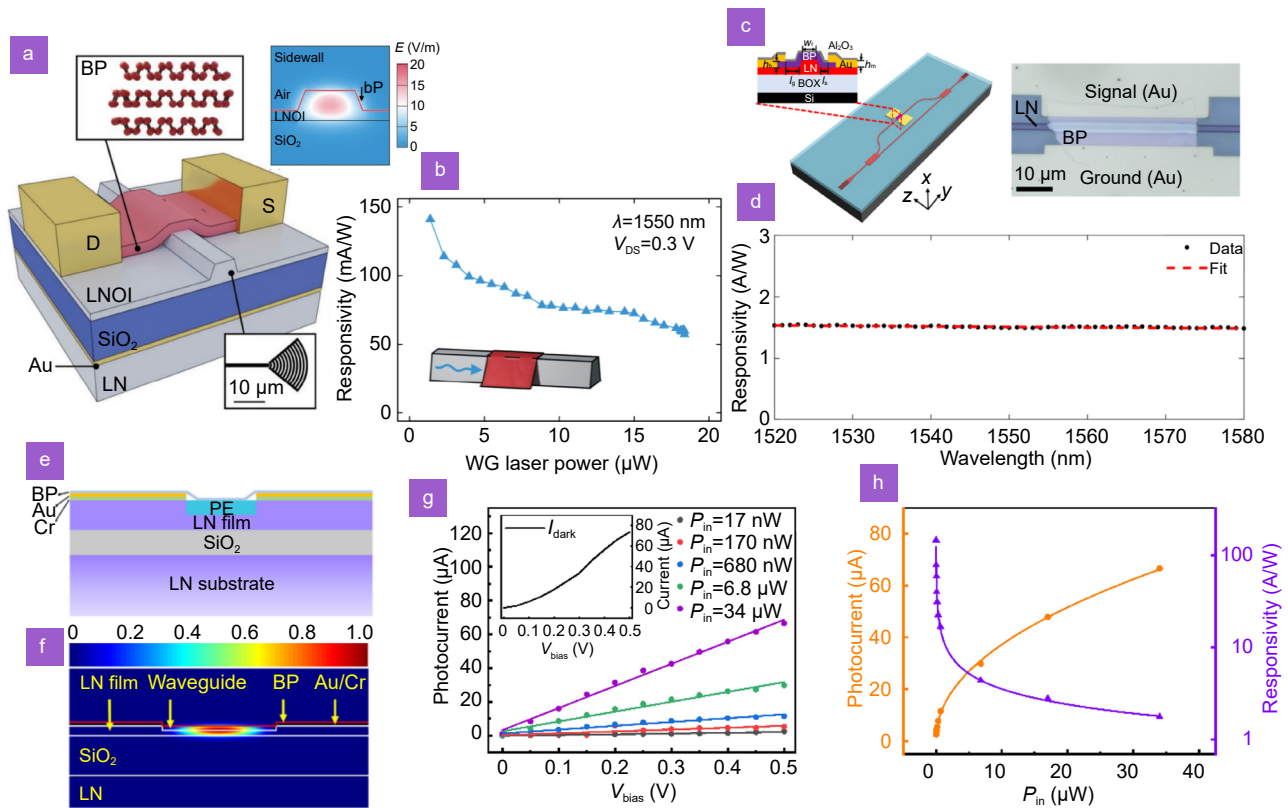


Fig. 7 | Performance of BP-TFLN hybrid photodetectors. (a) Device schematic of ridge TFLN waveguide integrated with BP photoconductor; inset shows simulated electromagnetic field of TE mode at 1550 nm. (b) Measured responsivity of BP-TFLN device. (c) Device schematic of Mach-Zehnder interferometer with grating couplers for input/output. (d) Wavelength dependence of photodetector responsivity. (e) Schematic of proton-exchanged TFLN waveguide device. (f) Electric field distribution of TE_{00} mode. (g) Photocurrent versus bias voltage. (h) Variation of photocurrent and responsivity. Figure reproduced with permission from: (a, b) ref.¹¹⁸ John Wiley and Sons; (c, d) ref.⁴², (e–h) ref.¹¹⁹, Optica Publishing Group.

2D materials¹²⁰. MoS_2 , with its tunable bandgap and strong light-matter interaction, complements BP to form a p - n junction that enhances charge separation and extraction. In 2024, Hu et al. reported a black phosphorus MoS_2 heterostructure photodiode integrated on an LNOI waveguide¹²¹, which exhibited low dark current (approximately 0.21 nA), a high on-off ratio (>200) under zero bias, and a responsivity of 1.46 A/W under -1 V bias.

Graphene, in comparison with BP, exhibits significantly higher carrier mobility—up to $20000\text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ among the highest for any 2D materials¹²². Combined with its broadband absorption, ultrafast carrier dynamics, and atomic thickness, graphene is well suited for high-speed and broadband photodetection. Although the lack of a bandgap limits responsivity, this challenge can be addressed by tuning the Fermi level, constructing heterostructures, or incorporating photonic structures that enhance interaction with light¹²³. In LNOI photonics, graphene integrated TFLN detectors have shown strong potentials. The evanescent field of the guided optical

mode interacts efficiently with the graphene layer, enabling broadband absorption ranging from the visible to the telecommunication bands. As shown in Fig. 8(a) and 8(b), this efficient coupling leads to pronounced optical attenuation within just a few tens of microns along the waveguide, highlighting the strong light absorption enabled by the graphene integration⁴⁷. Furthermore, the energy band diagram of the LNOI-graphene photodetector, illustrated in Fig. 8(c), reveals the presence of band bending and built-in electric fields at the interfaces between the graphene channel and the graphene beneath the gold electrodes. This is due to the difference in doping levels, where the graphene under the electrodes is p -doped and the exposed channel region becomes more heavily p^+ -doped due to environmental air exposure. Wang et al. have achieved the LNOI-Graphene photodetector, as shown in Fig. 8(d) and 8(e)⁴⁷. This structure enhanced light absorption and increased responsivity by 700% compared to devices based on pure graphene. The 3-dB bandwidth of this heterostructure was measured at

4.7 GHz, lower than that of pure graphene but still outperforming most other 2D material based TFLN detectors, reflecting a favorable trade-off between speed and sensitivity. Building on this approach, Cheng et al. realized an on-chip photodetector by integrating a graphene/Bi₂Te₃ heterostructure onto a TFLN waveguide fabricated via photolithography-assisted chemical mechanical etching¹²⁴. This Bi₂Te₃/graphene heterojunction device achieved a responsivity of 2.54 mA/W at a wavelength of 1.55 μm under zero external bias, representing a sevenfold improvement over a device based solely on graphene. Additionally, the detector maintained a 3-dB bandwidth exceeding 4.7 GHz, further validating the performance advantages of combining graphene with other functional materials in TFLN-based photonic systems.

Other 2D materials such as Te, Bi₂Te₃, and SnSe₂ have also been successfully integrated with TFLN waveguides, enabling enhanced light-matter interaction through evanescent field coupling¹²⁷. For example, a Te-based photodetector demonstrated a high responsivity exceeding 7 A/W at 1550 nm under zero bias, with a 3-dB bandwidth of 2 GHz, as shown in Fig. 9(a)⁴⁷, highlighting its potential for high-speed, low-power photodetection. Notably, the SnSe₂-TFLN photodetector, which employs a 35-nm-thick SnSe₂ layer covering a proton-exchanged TFLN waveguide, exhibits ultrasensitive bidi-

rectional photoresponse across a wide spectral range, as displayed in Fig. 9(b)¹²⁵. This device achieved a remarkably high responsivity of 761 A/W at 850 nm and maintains appreciable performance at telecom wavelengths, with a responsivity of 3.13 A/W at 1550 nm under a 1 V bias. In addition, it demonstrates sub-bandgap photore-sponse capabilities, attributed to defect-assisted absorption or evanescent field enhancement at the SnSe₂-TFLN interface. More recently, a Bi₂Te₃-TFLN photodetector array was demonstrated by Cheng et al., integrating a 4 $\times$ multi-mode interference (MMI) structure on a single chip to realize multichannel, self-powered detection, as shown in Fig. 9(c)¹²⁶. Post-electrothermal annealing of the Bi₂Te₃ layers significantly enhanced the device performance, enabling a responsivity of 60 mA/W at 1550 nm without bias. The fabricated PD arrays exhibited high uniformity across channels, highlighting their suitability for scalable, parallel optical data acquisition in PICs.

In summary, 2D materials-TFLN photodetectors represent a highly promising class of optoelectronic devices that combine the strong light-matter interaction and tunable electronic properties of 2D materials with the multifunctional capabilities of lithium niobate thin films. Table 1 summarized the photodetection performance of heterogeneously integrated 2D materials-LN photodetector. Both free-space illuminated and waveguide-integrat-

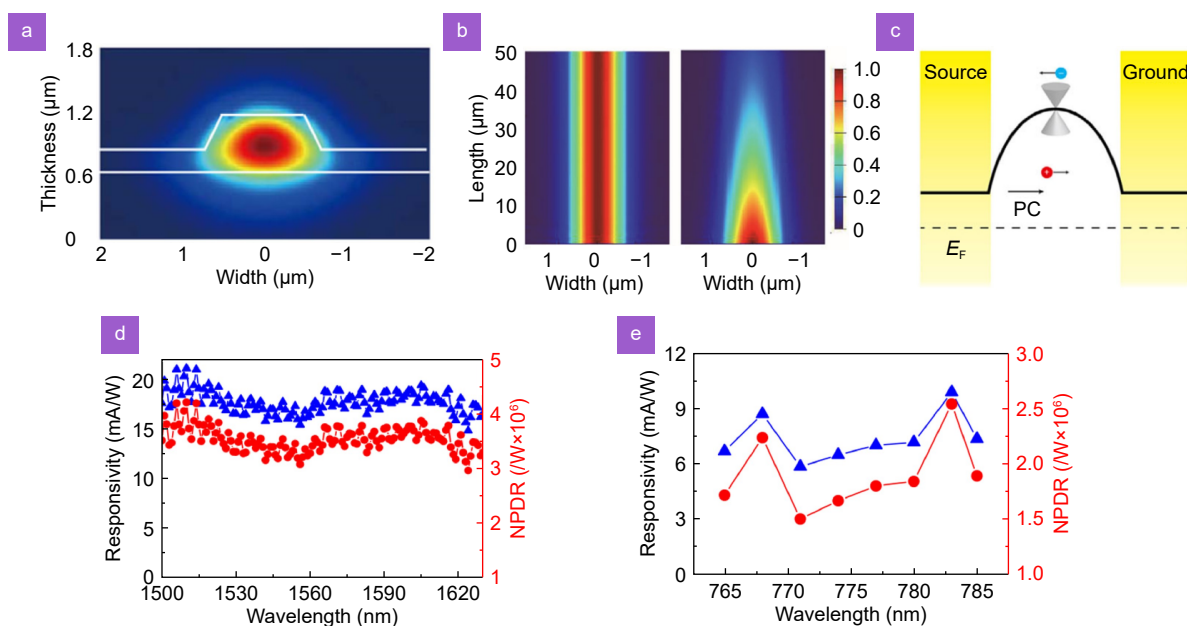


Fig. 8 | Performance of graphene-TFLN hybrid photodetectors. (a) Simulated optical eigenmode profile (electric field intensity) of LNOI waveguide. (b) Evolution of electric field intensity along LNOI waveguide without and with 10-layer graphene. (c) Energy band diagrams of LNOI-graphene photodetector (E_F : Fermi level; PC: photocurrent). (d, e) Measured responsivity and normalized photocurrent-to-dark current ratio (NPDR) at telecom and visible wavelengths under zero bias. Figure reproduced with permission from: (a–e) ref.⁴⁷, John Wiley and Sons.

ed configurations demonstrate unique advantages: the former leverages ferroelectric and pyroelectric effects for polarization-sensitive and broadband photodetection, while the latter offers enhanced light absorption efficiency, compact integration, and compatibility with photonic circuits. Continued advancements in material integration, device engineering, and structural optimization are expected to further push the performance boundaries of these heterostructure systems, paving the way for their application in high-speed optical communication, polarization-resolved sensing, on-chip logic, and quantum photonic technologies.

Heterogeneous single-photon detectors on TFLN platform

The integration of SPDs onto TFLN platforms is critical for advancing next-generation quantum photonic technologies, including quantum key distribution, quantum computing, and quantum sensing^{128–130}. These applications demand detectors that exhibit high quantum efficiency, low dark count rates, excellent timing resolution,

and seamless scalability within photonic integrated circuits. Among the various SPD technologies, superconducting detectors are particularly promising due to their unparalleled sensitivity, low noise characteristics, and precise timing performance¹³¹. Two leading approaches in this domain are transition-edge sensors (TESs) and superconducting nanowire single-photon detectors (SNSPDs)^{132,133}, both of which are being actively explored for heterogeneous integration with TFLN platforms, with SNSPDs currently showing more practical progress in integration.

Integrated TES on TFLN waveguide

TESs exploit the sharp resistance change near the superconducting critical temperature to detect single photons with high energy resolution^{134,135}. When a photon is absorbed, the resultant temperature increase causes a transition from the superconducting to the normal state, producing a measurable electrical signal. Owing to their intrinsic photon-number resolving capability and excellent energy sensitivity, TESs are well suited for quantum

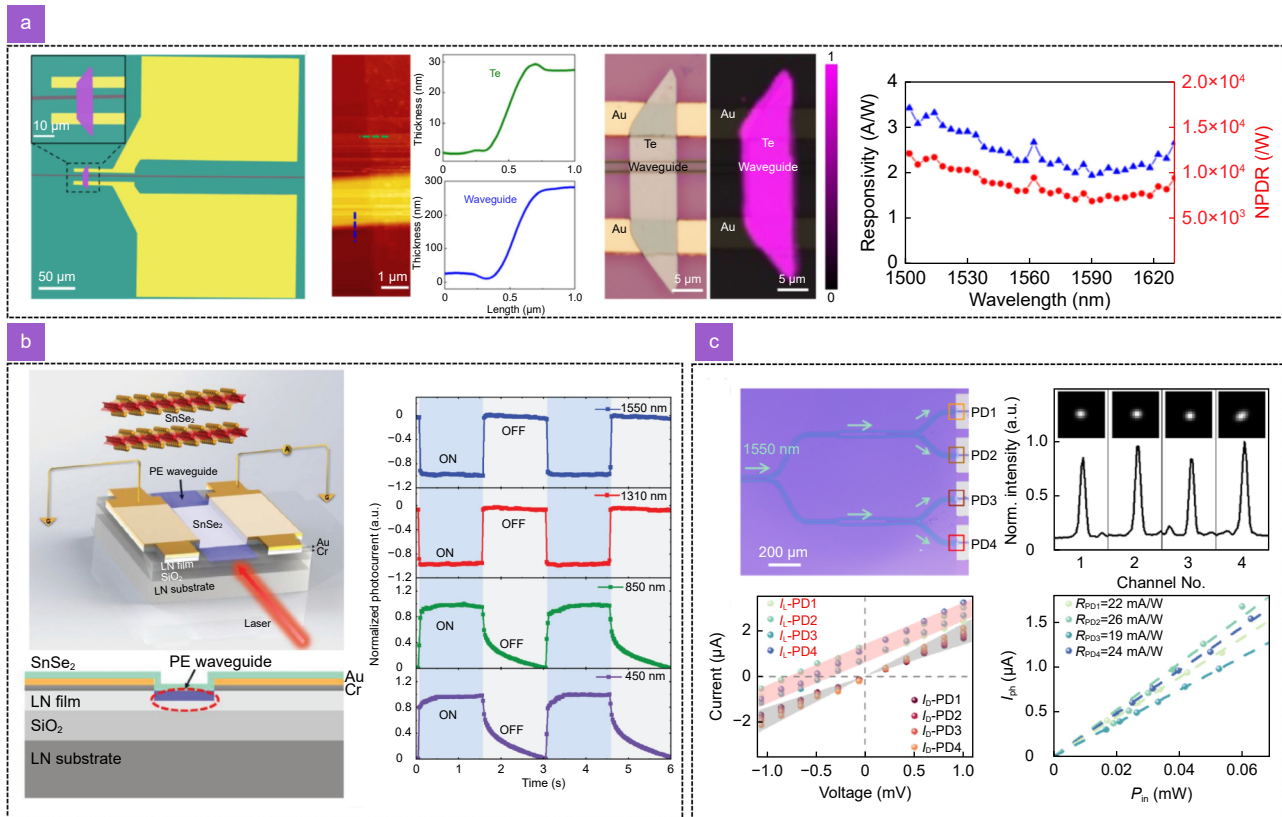


Fig. 9 | The Te, SnSe₂, and Bi₂Te₃-TFLN hybrid photodetector performance. (a) False-colored SEM, AFM, optical, Raman mapping images and responsivity of fabricated Te-LNOI photodetector. (b) Schematic and device performance of SnSe₂-TFLN photodetector. (c) Schematic illustration of 4× MMI structure based on Bi₂Te₃-TFLN platform and the output photocurrent for four channels. Figure reproduced with permission from: (a) ref.⁴⁷, (b) ref.¹²⁵, John Wiley and Sons; (c) ref.¹²⁶, Optica Publishing Group.

Table 1 | Progress in heterogeneously integrated 2D materials-LN photodetector technologies.

Illumination mode	Materials	Response wavelength (nm)	Responsivity (A/W)	Bias (V)	I_{on}/I_{off} ratio	3 dB bandwidth	Rise time (ms)	Refs.
Free-space illumination	Graphene	405–2000	1.78×10^5	0.5	/	/	3.3	ref. ⁴⁶
	WSe ₂	450	0.36	0	6.8×10^3	/	0.47	ref. ⁹⁷
	WS ₂	275–980	0.695 @ 0 V 55.6 @ 4		10^4	/	2	ref. ¹⁰³
	MoS ₂	633	113.1	5	/	/	32	ref. ¹⁰¹
	MoS ₂	365–1064	17.3	2	190	/	0.15	ref. ⁶⁸
Waveguide coupling	Graphene	765–785 1500–1630	0.017	0	3×10^6	40 GHz	/	ref. ⁴⁷
	Te	1500–1620	7	0.5	10^4	2 GHz	/	
	Black phosphorus	1510–1640	0.148	0.3	/	/	~100 ns	ref. ¹¹⁸
	Black phosphorus	450–1550	147	0.5	/	0.86 GHz	/	ref. ¹¹⁹
	Black phosphorus	1520–1580	2.64	2	/	1.97 GHz	/	ref. ⁴²
	MoS ₂ -BP heterostructure	1480–1580	1.46	–1	200	/	8	ref. ¹²¹
	Bi ₂ Te ₃ -Graphene heterostructure	1530–1600	0.00254	0	10^4	4.7 GHz	/	ref. ¹²⁴
	Graphene	1530–1600	0.36 mA/W	0	/	8.4 GHz	/	
	SnSe ₂	694.91 A/W @450 nm; 761.78 A/W @850 nm; 0.34 A/W @1310 nm; 3.13 A/W @1550 nm		1	/	16.4 Hz @ 1550 nm; 21.3@1550 nm; 17.5 Hz @ 1310 nm; 53.2@850 nm		ref. ¹²⁵
	Post-ETA Bi ₂ Te ₃	1550	0.06	0	/	/	0.01	ref. ¹²⁶
	MoTe ₂	1550	0.001	20	10^8	/	/	ref. ¹⁰⁵
	MoTe ₂	1260–1360	0.4	–3	/	>500 MHz	/	ref. ¹¹²
	MoTe ₂	1310	0.309	1	10^5	37 kHz	0.009	ref. ¹¹⁴
	MoTe ₂	1550	0.013	1	10^3	8 kHz	0.041	
	MoTe ₂	1310	0.07	0	10^4	2.2 kHz	0.16	ref. ¹⁰⁶
	MoTe ₂	1550	0.02 mA/W	0	/	/	0.153	
	MoTe ₂	1310	0.309	1	10^4	/	0.009	ref. ¹¹⁴
	MoTe ₂	1550	0.013	1	10^3	/	0.041	

optics applications. A recent proof-of-principle study has demonstrated the integration of TESs with titanium indiffused LN waveguide *via* evanescent coupling¹³⁶, achieving on-chip single-photon detection by Bartley TJ et al. The histogram of the measured photon response traces confirmed the photon-number resolution, and the system exhibited strong polarization sensitivity when light was coupled from both ends of the waveguide into two detectors, as shown in Fig. 10(a). The TES response was optimized by changing the polarization setting and monitoring the mean photon number using an in situ histogramming. As displayed from Fig. 10(b), from the room-temperature loss measurements and simulations, the maximum system detection efficiency (SDE) was related to TM-polarization and the minimum SDE to TE-polarization.

Although the detection efficiency of this architecture

remains to be optimized, several strategies have been proposed to enhance performance. These include extending the interaction length through the addition of tungsten fins to conduct heat more effectively to the TES, tapering the LN waveguide to increase mode confinement, and introducing dielectric cladding layers to pull the optical mode closer to the detector surface for improved absorption. Simulations have shown that such modifications can significantly enhance evanescent coupling¹³⁶. Furthermore, detector multiplexing is a promising approach to improve scalability and system-level detection efficiency. While it remains an open question whether evanescently coupled TESs on TFLN can outperform conventional end-fire-coupled devices, their compatibility with dense on-chip integration holds substantial promise for future quantum photonic processor architectures.

SNSPDs on TFLN waveguide

SNSPDs are among the most advanced technologies in the field of single-photon detection, offering an impressive combination of high SDE, low timing jitter, ultra-low

dark count rates, and high maximum count rates^{132,137–139}.

These exceptional attributes make SNSPDs ideal for a wide array of applications in quantum communication, photonic quantum computing, and time-correlated

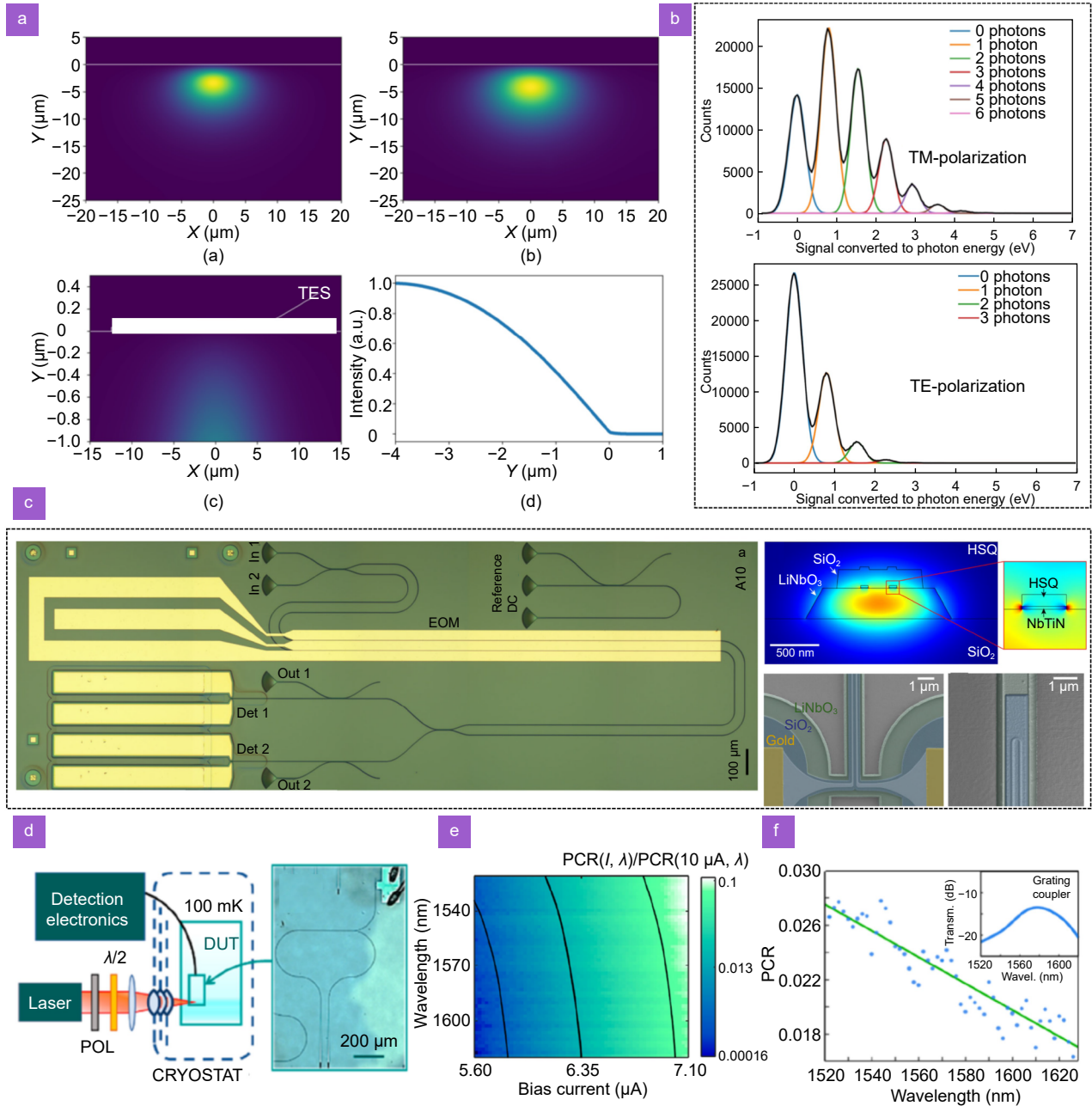


Fig. 10 | Heterogeneous single-photon detectors on TFLN platform. (a) Simulated polarization modes of titanium in-diffused LN waveguide: TM-polarized guided modes (left) and TE-polarized modes (right). (b) Histograms of photon traces converted to photon energies for one detector, with Gaussian fits for TM and TE polarization peaks. (c) Overall chip layout and experimental system; includes optical microscope image of integrated device with directional coupler, waveguide-integrated SNSPDs design and absorption simulation, plus SEM and AFM images of fabricated detectors near U-turn and electrodes. (d) Waveguide-based measurement setup schematic; normalized photon count rate versus bias current and timing jitter for NbTiN SNSPDs on 300 nm-thick TFLN ridge waveguides. (e) Photon count rate (PCR) map showing normalized responsivity across wavelengths and bias currents; averaged contour lines highlight trends. (f) PCR data (blue dots) with linear fit (green line); inset shows simulated coupling efficiency of grating couplers based on AFM measurements. Figure reproduced with permission from: (a, b) ref.¹³⁶, (d–f) ref.¹⁴⁷, AIP Publishing; (c) ref.³⁶, Nature.

single-photon counting, all of which require precise and efficient detection of individual photons¹⁴⁰. The fundamental operation of SNSPDs is based on the principle of superconductivity¹³³. The detector consists of a superconducting nanowire that is biased just below its critical current. When a photon is absorbed by the nanowire, it induces a localized resistive hotspot, temporarily disrupting the superconductivity of the wire. This disruption results in the generation of a voltage pulse that can be measured, signaling the detection of a photon.

As the demand for scalable quantum photonic systems continues to grow, considerable effort has been dedicated to the integration of SNSPDs onto TFLN platforms^{141–144}. TFLN is an attractive material for quantum photonics due to its strong optical confinement and high refractive index contrast, which makes it ideal for efficient evanescent coupling between the guided optical modes and the superconducting nanowire that is typically patterned on top of the waveguide. TFLN-based waveguides enable precise control of light propagation, facilitating the integration of SNSPDs with high-efficiency photon coupling. Integration strategies generally involve the direct deposition of superconducting materials such as niobium nitride (NbN), niobium titanium nitride (NbTiN), tungsten silicide (WSi), or molybdenum silicide (MoSi) onto pre-fabricated ridge or strip-loaded TFLN waveguides^{36,141,145–147}. Following deposition, high-resolution electron-beam lithography and reactive ion etching are used to define nanowires with widths on the order of 100 nm or less. In 2020, Tang et al. demonstrated waveguide-integrated SNSPDs on TFLN, achieving a detection efficiency exceeding 46% at telecom wavelengths, with an impressively low timing jitter of 32 ps and dark count rates as low as 13 Hz¹⁴¹. The team utilized bidirectional waveguide excitation for orthogonal polarization modes, ensuring efficient coupling of 1550 nm photons into the detector, which verified the feasibility of integrating SNSPDs directly onto TFLN waveguides while maintaining the high performance typically seen in standalone SNSPDs. In 2021, SNSPDs have been integrated into lower-loss LNOI waveguide networks. The optical microscope image of the integrated device is shown in Fig. 10(c)³⁶. These advancements represent a crucial step toward the realization of practical quantum photonic integration, where the integration of SNSPDs into ultralow-loss waveguides (with a loss as low as 0.2 dB/cm) allows for high-performance quantum operations within a compact footprint. The NbTiN nanowires

were directly fabricated on the TFLN waveguides, achieving nearly saturated internal quantum efficiency and timing jitter comparable to that of standalone SNSPDs, demonstrating that the integration method does not compromise detector performance.

One of the most exciting aspects of these recent integrations is the ability to co-integrate SNSPDs with high-speed active components such as electro-optic modulators. This capability is essential for developing reconfigurable quantum photonic processors, where both detection and modulation can be performed on the same chip. The use of compact waveguide bends, with radii smaller than 100 μm , further enhances the potential for dense photonic circuit layouts. This flexibility in design is crucial for scaling up quantum systems and moving toward fully reconfigurable and scalable quantum processors. These developments have paved the way for the next generation of quantum photonic platforms, which will feature a high degree of integration, allowing for more complex, yet efficient, quantum circuits.

Beyond photon detection, SNSPDs integrated onto TFLN waveguides have shown remarkable potential for on-chip wavelength discrimination. In a 2023 study, hairpin-shaped SNSPDs were fabricated on single-mode *x*-cut lithium niobate waveguides and utilized as on-chip wavelength meters, as shown in Fig. 10(d)¹⁴⁷. These detectors were able to resolve photon wavelengths across the 1520–1630 nm range. This innovative approach takes advantage of the wavelength-dependent responsivity of SNSPDs, which can be explained by the hotspot model. In this model, the resistive region created when a photon is absorbed grows in size with increasing photon energy, and the count rate thus becomes dependent on the wavelength of the incident photons, as illustrated in Fig. 10(e). By measuring the count rates under varying bias currents, the wavelength of the incoming photons can be inferred without the need for external dispersive optical elements. This technique allows for the creation of compact, spectrally resolved quantum circuits, offering a powerful tool for wavelength-multiplexed quantum photonics, as shown in Fig. 10(f).

The most recent advancement in this area, a 2024 study, demonstrated the integration of amorphous MoSi SNSPDs onto TFLN waveguides using standard fabrication processes, as shown in Fig. 11(a)¹⁴⁵. The MoSi-based SNSPDs achieved an on-chip detection efficiency of approximately 50% at 1550 nm, with a timing jitter of 82 ps measured at a temperature of 0.78 K. Importantly, this

integration was achieved using conventional fabrication techniques, without the need for stringent cooling or specialized substrate requirements, making it much easier to scale the technology for use in large-scale quantum systems. This breakthrough not only reinforces the suitability of TFLN for hosting high-performance SNSPDs but also expands the range of superconducting materials that can be integrated into complex, fully integrated quantum photonic platforms. These advancements underscore the growing potential of SNSPDs as key components in the development of integrated quantum photonic systems, pushing forward the vision of reconfigurable, scalable quantum processors capable of tackling the challenges of future quantum technologies.

The integration of SNSPDs into TFLN platforms is a major step forward in the realization of scalable, integrated quantum photonic circuits. Through continuous improvements in fabrication techniques and integration strategies, SNSPDs have the potential to play a pivotal role in the development of future quantum technologies, offering high-performance detection, wavelength discrimination, and low-loss photon routing on a single chip. As research progresses, these integrated systems will likely become the backbone of next-generation quantum communication and quantum computing technologies.

Frequency up-conversion detection

Frequency up-conversion detection utilizes the strong second-order nonlinear susceptibility of LN to convert long-wavelength photons, typically in the MIR or telecommunication bands, into shorter-wavelength photons within the NIR or visible range, where high-performance and cost-effective silicon-based single-photon detectors are readily available⁷⁷. This method effectively overcomes the limitations of conventional infrared detectors, which often exhibit high dark count rates, low detection efficiency, and a requirement for cryogenic operation. By transducing photon energies into a spectral region compatible with mature detector technologies, frequency up-conversion provides a promising route toward highly efficient and low-noise single-photon detection.

Recent proof-of-concept demonstrations on LNOI platforms have successfully realized on-chip nonlinear frequency conversion coupled with off-chip photodetection^{76, 148–150}. These studies underscore the inherent advantages of LNOI, including its high nonlinear coefficient,

broad transparency window, and compatibility with quasi-phase matching via periodic poling. As illustrated in Fig. 11(b), Wang et al. developed an up-conversion single-photon detector operating in the telecommunication band based on a quantum frequency conversion (QFC) chip, achieving an average detection efficiency of 8.7% with a noise count rate of 300 cps⁷⁶. This on-chip low-noise and high-efficiency quantum frequency converter highlights the potential for heterogeneously integrated chip-scale QFC systems. Nevertheless, to realize compact and robust systems, full integration of both nonlinear frequency conversion and detection functionalities on a single chip remains essential.

More recently, He et al. demonstrated a pioneering photonic up-conversion detection chip where near-infrared light is converted to visible wavelengths in a periodically poled LNOI section, and the up-converted signal is detected using a heterogeneously integrated amorphous silicon (α -Si) photodetector operating at room temperature, as displayed in Fig. 11(c)⁴⁰. The measured responsivity of the integrated detector for the converted visible light reached 95 mA/W under a 4 V bias. Further improvements in conversion efficiency are anticipated through optimized periodic poling designs, which would consequently reduce operating power requirements. In such integrated architectures, MIR or telecom photons entering the waveguide can be efficiently up-converted to visible light via tailored quasi-phase matching, and subsequently detected by a co-located on-chip photodetector with minimal propagation loss. Such monolithic integration not only eliminates coupling losses associated with external detectors but also significantly enhances system stability and scalability, critical attributes for the deployment of large-scale quantum networks.

Direct modified TFLN detector

Heterogeneously integrated TFLN photodetectors have achieved enhanced responsivity and extended spectral coverage by incorporating external functional materials. However, they often suffer from complex fabrication processes, interfacial stability issues, and limited compatibility with CMOS technology. As a promising alternative, directly modified TFLN photodetectors harness the intrinsic pyroelectric, piezoelectric, and photo-thermoelectric properties of LN, offering simplified architectures with improved structural robustness and integration potential.

Early advancements in this field were reported in 2001,

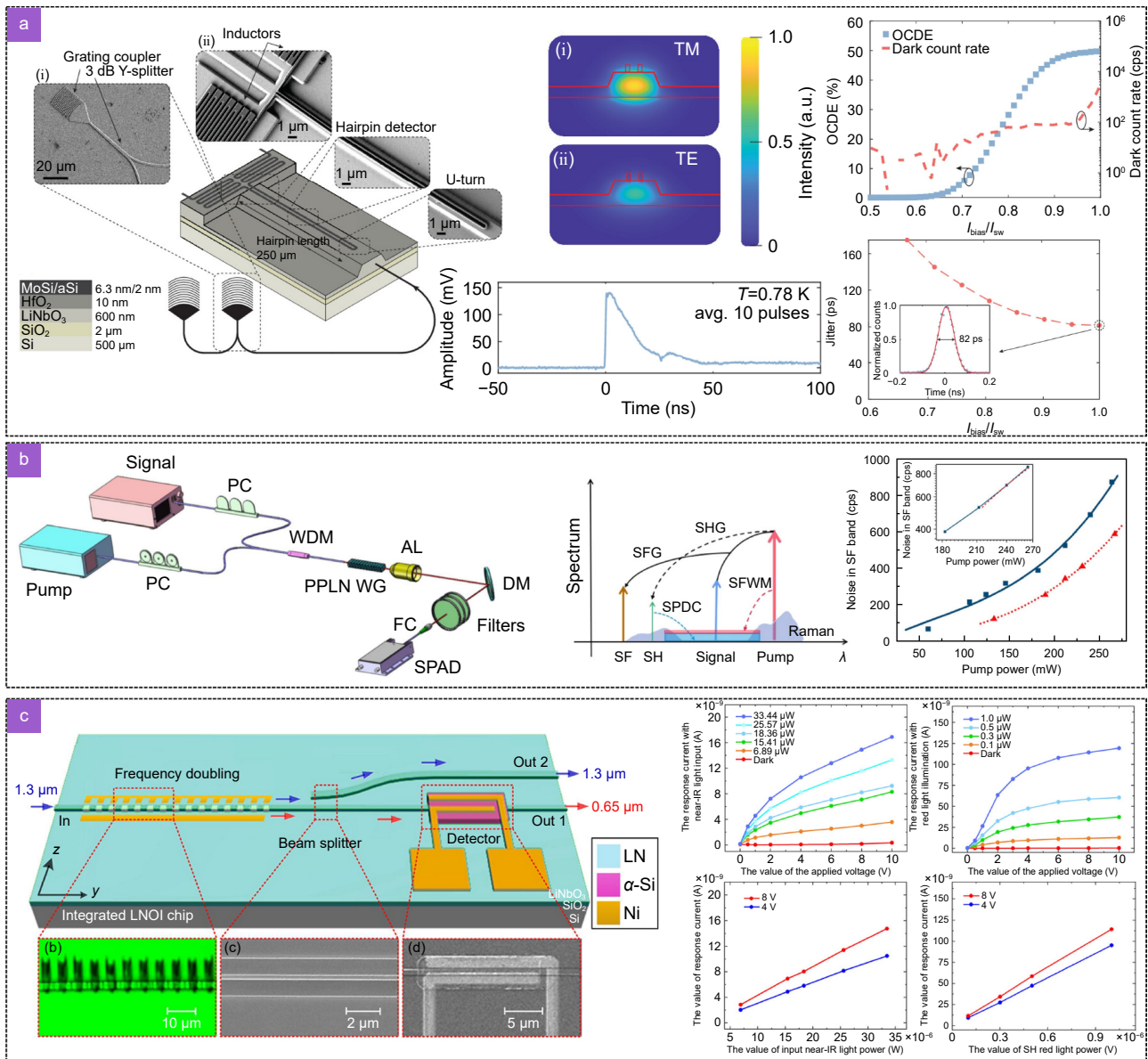


Fig. 11 | Performance characterization and measurement setup of the integrated superconducting nanowire SNSPD on a LN waveguide platform. (a) Device architecture, scanning electron microscopy images, and performance metrics of MoSi-based SNSPDs integrated on LN waveguides. (b) Schematic of up-conversion on an LNOI chip followed by detection with a silicon single-photon detector. (c) A multifunctional LNOI photonic chip integrating both frequency up-conversion and photodetection capabilities. Figure reproduced with permission from: (a) ref.¹⁴⁵, (c) ref.⁴⁰, ACS Publishing; (b) ref.⁷⁶, Nature.

demonstrating that *z*-cut LN wafer-based pyroelectric detectors could be fabricated with reduced sensitivity to acoustic noise and ambient temperature variations through domain engineering, without compromising optical responsivity¹⁵¹. The detector exhibited a noise equivalent power (NEP) of $6 \text{ nW} \cdot \text{Hz}^{-1/2}$ at 16 Hz and a temperature-dependent response variation of only 0.1%/K near room temperature. Building on this foundation, Yu et al. further enhanced the pyroelectric performance by doping LN with tantalum (Ta) ions, achieving a high voltage

responsivity of 7020 V/W at 70 Hz and a specific detectivity of $7.76 \times 10^7 \text{ cm} \cdot \text{Hz}^{1/2} / \text{W}$ at 200 Hz using $\text{LiNb}_{0.8}\text{Ta}_{0.2}\text{O}_3$ (LNT) thin films¹⁵². These results highlight the critical role of ion doping in tailoring the functional properties of lithium niobate for enhanced photodetection performance. In a recent study published in 2023, magnesium (Mg)-doped bulk LN (Mg:LN) photodetectors demonstrated significantly enhanced response speed and performance³³. Compared to conventional pyroelectric LN photodetectors, which typically

have response speeds limited to around 100 Hz, these Mg:LN devices achieved response speeds up to 10 kHz, as shown in Fig. 12(a). However, as illustrated in Fig. 12(b), the photocurrent and responsivity of the Mg:LN photodetectors were slightly reduced compared to undoped congruent LN photodetectors. This reduction is attributed to the decreased number of bipolaron donor centers in Mg:LN, resulting from the substitution of Nb_{Li} sites by Mg^{2+} dopants.

Our group proposed the use of ion beam modification techniques for TFLN in 2022⁴⁵. Ion beam processes enable precise control over doping, defect engineering, and synthesis of functional nanostructures, while remaining fully compatible with existing TFLN fabrication technology^{153–154}. These methods allow for engineering of sub-bandgap absorption, localized refractive index modulation, and the formation of embedded plasmonic nanostructures, thereby expanding the photodetection mechanisms of TFLN beyond conventional thermal effects¹⁵⁵. By selecting the typical ion species, energy, and fluence, the band structure through the introduction of defect states and localized energy levels can be tailored, facilitating photoelectric or photoconductive response in an otherwise wide-bandgap dielectric material. Metal ion implantation (e.g., Au or Ag) into TFLN enables the formation of metallic nanoparticles distributed near a few nanometers of top surface^{156–159}, which exhibit LSPR and dramatically enhance light-matter interaction. The device fabrication process and cross-sectional transmission electron microscopic of ion implanted LNOI are shown in Fig. 12(c). Leveraging this approach, a self-powered LNOI thin-film photodetector was recently demonstrated, achieving broadband response from 473 nm to 1900 nm, a high on/off ratio of 6000, specific detectivity of 1.56×10^{14} Jones, and responsivity of 0.25 A/W, representing the first self-powered photodetector monolithically integrated on an LNOI chip without any additional photosensitive layers. Figure 12(d) exhibits the photodetection performance from visible to near-infrared region. Furthermore, ion beam-modified TFLN can serve as a functional substrate for enhancing 2D material-based photodetection, and similar ion-beam strategies have also been validated in lithium tantalate, another ferroelectric material with structural similarity to lithium niobate^{160,161}.

In a recent example, Zhang et al. developed directly modified TFLN Lamb wave mode resonators IR detection based on z-cut 750 nm-thick TFLN¹⁶². These de-

vices utilize thermoelastic modulation of anti-symmetric acoustic modes (A_1 , A_3 , A_5 , A_7) under modulated IR illumination. Under an IR power of 0.575 mW, distinct admittance changes near anti-resonance frequencies were observed with minimal frequency drift, attributed primarily to photothermal-induced changes in static capacitance rather than direct photocarrier excitation. The A_1 mode exhibited a NEP of 15.41 pW/Hz^{1/2} and a specific detectivity of 7.40×10^6 m·Hz^{1/2}/W, surpassing those of conventional GaN, ZnO, and AlN resonator-based detectors.

Direct modification strategies provide a powerful and versatile approach to unlock the intrinsic optoelectronic potential of TFLN without relying on external materials or complex heterostructures. By leveraging techniques such as domain engineering, ion beam modification, and resonant device design, researchers have demonstrated significant advancements in sensitivity, spectral response, and integration compatibility. These developments not only expand the functional landscape of TFLN photodetectors but also pave the way for monolithic, CMOS-compatible on-chip sensing systems with broadband and multifunctional detection capabilities.

Summaries and perspectives

The evolution from bulk LN to TFLN has markedly enhanced optical confinement and integration potential, providing a solid foundation for the next generation of on-chip photonic devices^{163–166}. As essential components for converting optical signals into electrical ones, photodetectors underpin a wide range of integrated photonic applications, including optical interconnects, quantum information processing, and advanced sensing systems. This review has outlined the fundamental photodetection mechanisms of lithium niobate, recent progress in direct modification techniques such as ion implantation and defect engineering, and emerging hybridization strategies involving 2D materials and III-V semiconductors. Both heterogeneous integration and direct modification present effective but distinct pathways to extending the photodetection capabilities of TFLN-based devices.

Heterogeneous integration involves coupling TFLN with external functional materials such as III-V semiconductors, silicon, or 2D materials. This approach enables a synergistic combination of material properties, significantly broadening the spectral response by leveraging strong optical absorption and efficient carrier transport, while preserving TFLN's inherent advantages in

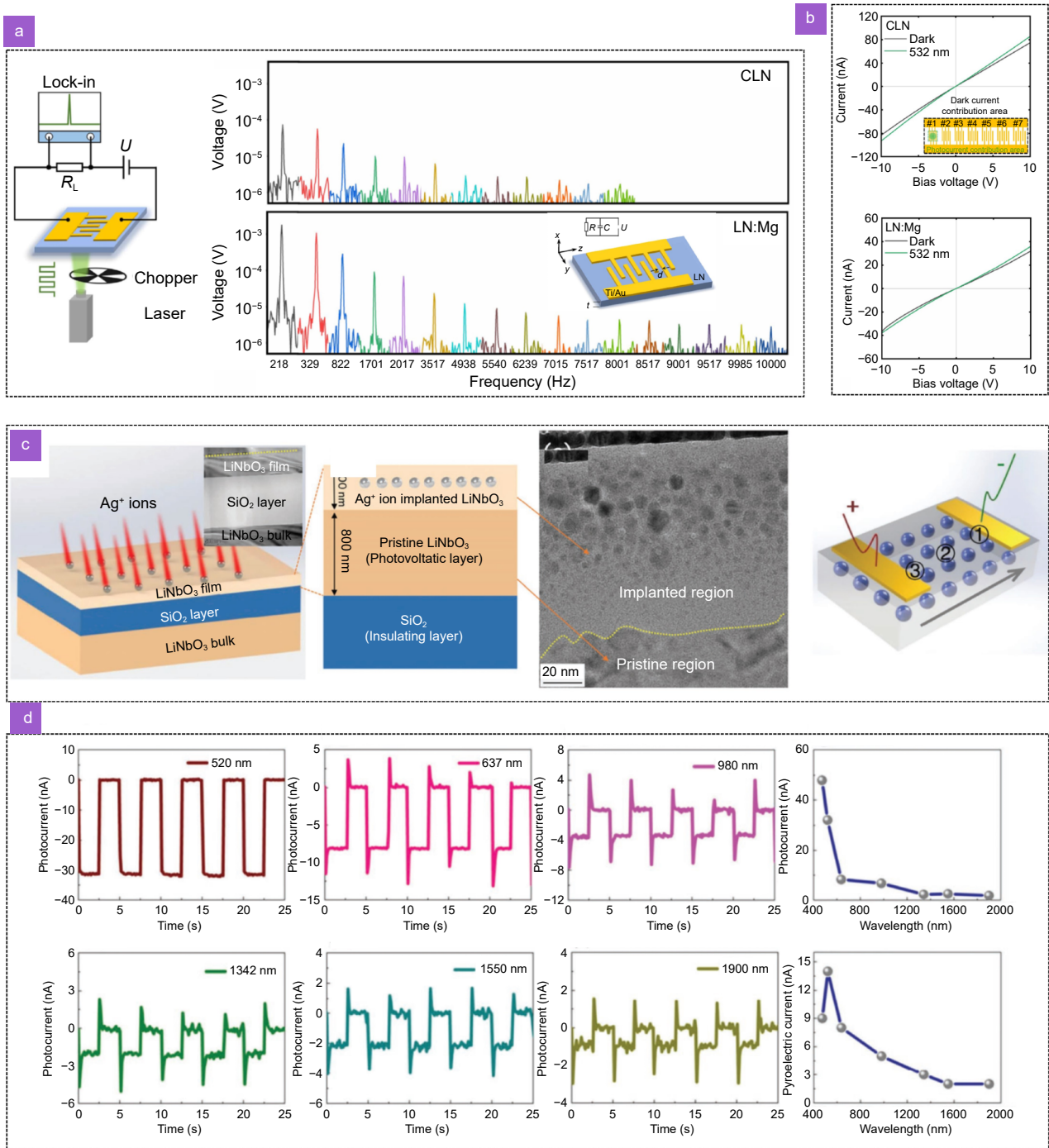


Fig. 12 | Direct modification approaches for LN-based photodetectors. **(a)** Frequency response of CLN and Mg:LN photodetectors. **(b)** Current-voltage (I - V) characteristics of CLN and Mg:LN photodetectors. **(c)** Structural and morphological characterization of LNOI devices modified by Ag ion implantation. **(d)** Photodetection performance of Ag ion-implanted LNOI photodetector. Figure reproduced with permission from: (a, b) ref.³³, (c, d) ref.⁴⁵, John Wiley and Sons.

waveguiding, electro-optic modulation, and ferroelectric functionality. Regarding device configuration, free-space optical incidence and waveguide coupling each have distinct advantages: free-space incidence is structurally simple, allows rapid characterization and flexible coupling

with external light sources, and is suitable for large-area detection or non-contact sensing. However, it generally suffers from limited coupling efficiency and integration density, making it less ideal for highly compact, fully integrated systems. In contrast, waveguide coupling

enables seamless integration with on-chip photonic circuits, providing higher coupling efficiency, system compactness, and suitability for high-speed interconnects, on-chip logic, and quantum photonic applications. Nevertheless, waveguide-based devices demand higher fabrication precision, uniformity, and careful management of coupling losses. Therefore, free-space incidence is better suited for prototyping, broadband detection, and flexible testing, while waveguide coupling is advantageous for high-performance, scalable, and fully integrated photonic systems.

Direct modification strategies, including ion implantation, defect engineering, and nanoparticle incorporation, allow localized tuning of TFLN's optical, electrical, and structural properties without relying on external materials. These techniques can introduce plasmonic resonances, modify refractive indices, and generate internal electric fields to promote photocarrier dynamics. Directly modified TFLN structures often exhibit improved mechanical stability, enhanced integration density, and compatibility with standard fabrication techniques, while mitigating many interface-related challenges inherent in heterogeneous approaches. However, spectral tunability is relatively limited, and the achievable broadband response or responsivity may not match that of hybrid systems. The wide bandgap of lithium niobate imposes intrinsic absorption constraints, and performance enhancement strongly depends on the precision of modification parameters. Some methods, such as high-dose ion irradiation or metal nanoparticle embedding, may also introduce optical loss or long-term stability issues.

The optimal strategy depends on application-specific requirements. Heterogeneous integration is particularly suitable for high-performance, broadband, and multifunctional photodetectors, where the properties of added materials can be independently optimized. In contrast, direct modification is advantageous for compact, monolithic designs that prioritize structural simplicity and process efficiency. A promising direction for future development lies in combining these two approaches. For example, integrating 2D materials onto pre-modified or plasmonically enhanced TFLN substrates may achieve a balance between responsivity, spectral flexibility, and structural compactness, offering a viable path toward next-generation photonic integration.

Looking forward, TFLN-based photodetectors are expected to remain critical components in photonic integrated circuits, not only serving as signal transducers but

also enabling optical logic functions, on-chip analysis, and real-time sensing. The rising demand for ultrafast, energy-efficient, and highly integrated photonic systems will continue to drive research toward monolithic platforms in which photodetectors are seamlessly integrated with light sources, modulators, and waveguides on a single TFLN chip. Realizing such multifunctional integration represents an essential step toward building fully integrated photonic systems capable of advanced on-chip signal processing. However, several key challenges must be addressed. Optical loss arising from modification processes or material interfaces remains a critical bottleneck, while fabrication scalability and device uniformity determine the feasibility of large-scale deployment. Full CMOS compatibility is also essential for bridging photonic and electronic platforms. Potential solutions include adopting advanced nanofabrication techniques to improve patterning precision and yield; leveraging AI-assisted inverse design and optimization to explore device geometries with reduced loss and enhanced performance; and hybrid integration with silicon photonics to utilize mature fabrication ecosystems and ensure CMOS compatibility.

Future research may further focus on developing innovative hybridization approaches, metasurface-enabled light manipulation techniques, and advanced packaging architectures that facilitate complete photonic-electronic integration. Within this framework, TFLN emerge as a uniquely versatile platform for implementing intelligent photonic systems spanning communications, computing, sensing, and quantum technologies.

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Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 12235009, 12134009) and Open fund (SKLMRD-K202522) of the State Key Laboratory of Chemical Reaction Dynamics in DICP, CAS. F Chen and YC Jia acknowledge the support from Taishan Scholars Program of Shandong Province. XL Sun acknowledges the support from "Qilu Young Scholar Program" of Shandong University, China.

Competing interests

Feng Chen serves as an Editor for the Journal, no other author has reported any competing interests.



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