

# Hyperdoped silicon photodetectors enable room-temperature computational SWIR imaging at 1550 nm

**Xiaolong Liu**

`xiaolong.liu@aalto.fi`

Aalto University <https://orcid.org/0000-0002-1976-492X>

**Sören Schäfer**

Institute for Microtechnologies (IMtech), RheinMain University of Applied Sciences

**Jinyuan Chen**

Department of Electrical and Electronic Engineering, University of Melbourne

**Patrick Mc Kearney**

Institute for Microtechnologies (IMtech), RheinMain University of Applied Sciences

<https://orcid.org/0000-0002-5243-4295>

**Simon Paulus**

Institute for Microtechnologies (IMtech), RheinMain University of Applied Sciences

**Varsha Vedaraj**

Department of Electrical and Electronic Engineering, University of Melbourne <https://orcid.org/0009-0004-1598-082X>

**Ville Vähänissi**

Aalto University <https://orcid.org/0000-0002-2681-5609>

**Stefan Kontermann**

Institute for Microtechnologies (IMtech), RheinMain University of Applied Sciences

**Kenneth Crozier**

University of Melbourne <https://orcid.org/0000-0003-0947-001X>

**James Bullock**

University of Melbourne

**Hele Savin**

Aalto University <https://orcid.org/0000-0003-3946-7727>

---

**Article**

**Keywords:**

**Posted Date:** July 3rd, 2026

**DOI:** <https://doi.org/10.21203/rs.3.rs-9689386/v1>

**License:** © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.  
[Read Full License](#)

**Additional Declarations:** There is no conflict of interest

---

# Hyperdoped silicon photodetectors enable room-temperature computational SWIR imaging at 1550 nm

Xiaolong Liu<sup>1,2,\*</sup>, Sören Schäfer<sup>3</sup>, Jinyuan Chen<sup>2</sup>, Patrik Mc Kearney<sup>3</sup>, Simon Paulus<sup>3</sup>, Varsha Ashwin Vedaraj<sup>2</sup>, Ville Vähänissi<sup>1</sup>, Stefan Kontermann<sup>3</sup>, Kenneth Crozier<sup>2,4,5</sup>, James Bullock<sup>2</sup>, Hele Savin<sup>1</sup>

1. Department of Electronics and Nanoengineering, Aalto University, 02150 Espoo, Finland

2. Department of Electrical and Electronic Engineering, University of Melbourne, Victoria 3010, Australia

3. Institute for Microtechnologies (IMtech), RheinMain University of Applied Sciences, Am Brückweg 26, 65428 Rüsselsheim, Germany

4. ARC Centre of Excellence for Transformative Meta-Optical Systems (TMOS), University of Melbourne, Victoria 3010, Australia

5. School of Physics, University of Melbourne, Victoria 3010, Australia

\* Correspondence: Xiaolong Liu (xiaolong.liu@aalto.fi)

## Abstract

Silicon's bandgap inherently restricts its photodetection to wavelengths below 1100 nm, necessitating the integration of costly III-V semiconductors for short-wave infrared applications. Hyperdoping silicon beyond the solid solubility limit offers a promising “silicon-native” alternative, yet achieving practical short-wave infrared applications at room temperature remains a formidable challenge. Here, we demonstrate a high-detectivity hyperdoped silicon photodetector enabling room-temperature computational short-wave infrared imaging beyond Si bandgap wavelength at  $\lambda = 1550$  nm. By integrating an ultrafast laser heating process step to reduce the dark current while keeping high responsivity, we achieve a specific detectivity  $D^*$  exceeding  $10^9$  Jones for 1550 nm at room temperature working in a forward-biased, photoconductive mode. The improved detectivity, coupled with a 59.4 dB linear dynamic range and kHz-scale bandwidth, allows us to demonstrate a single-pixel imaging system that reconstructs 1550 nm scenes at  $65 \times 63$  pixels without cryogenic cooling. Our devices simultaneously support visible-light imaging, offering a path toward monolithically integrated, multispectral Si-native optical sensors. These results establish ultrafast-laser hyperdoped silicon as a viable platform for low-cost, room-temperature, short-wave infrared photonics, bridging the gap between advanced materials science and practical computational imaging system.

## Introduction

Silicon is the workhorse of modern electronics and photonics, yet its bandgap confines conventional Si photodetectors to wavelengths below  $\lambda = 1100$  nm. This precludes direct detection in short-wave infrared (SWIR) that is increasingly exploited, e.g., in fiber networks<sup>1–3</sup>, imaging/LiDAR<sup>4–7</sup>, biochemical sensing<sup>8–10</sup> and free-space optical

communication<sup>11–13</sup>. Other than silicon, accessing the SWIR with mature technologies typically requires compound semiconductors such as PbS, InGaAs and GaSb, which are toxic, expensive, difficult to monolithically integrate with Complementary Metal–Oxide–Semiconductor (CMOS) technology, and often rely on complex epitaxial growth or cooling<sup>14–16</sup>. These constraints hinder the development of large-area, low-cost SWIR imagers and integrated photonic–electronic systems. The fundamental challenge remains whether silicon can be engineered beyond its intrinsic bandgap limitations to achieve the sufficiently-high sub-bandgap performance required for practical, room-temperature SWIR applications without the need for heterogeneous integration.

Hyperdoping provides a conceptually attractive route for trials in extending silicon’s spectral reach<sup>17–26</sup>. By introducing deep-level impurities at concentrations far beyond equilibrium solid solubility, hyperdoping creates intermediate-band states that enable sub-bandgap absorption and, in principle, SWIR detection using standard silicon wafers and CMOS-compatible processes. A variety of hyperdoped-Si devices have demonstrated room-temperature response beyond 1100 nm (**Supplementary Table S1**), but most work has focused near ~1000–1350 nm, where peak responsivity is located or high enough responsivity can be achieved at the expense of millisecond response times<sup>24,25,27</sup>. By contrast, systematic characterization at longer wavelengths remains sparse: reported responsivities are typically very low<sup>20–22</sup>, often not even fully quantified or they are enabled by deep-cooling<sup>23</sup>. Moreover, practical device metrics such as noise, bandwidth and detectivity are rarely reported for longer SWIR wavelengths. This is partly because responsivities at longer wavelengths are generally much ( $\sim > 3$  orders of magnitude) lower than peak responsivity at ~1000 nm, and often not comprehensively measured, either due to instrumental limitations or historical assumptions that performance at longer wavelengths is too limited to be practically relevant. As a result, across the family of hyperdoped silicon materials and devices, performance at longer SWIR bands remains under-explored and under-exploited for practical applications.

Beyond fundamental material metrics, validating the viability of hyperdoped silicon requires a demonstration of performance in practical, high-demand sensing scenarios. Computation-based single-pixel imaging (SPI), which integrates spatial light modulation with a single non-pixelated sensor, serves as an ideal benchmark. It provides a stringent system-level test of a detector’s detectivity, noise profile, and bandwidth without the overhead of fabricating complex focal plane arrays. To date, however, SWIR SPI implementations have largely relied on compound semiconductors or emerging thin-film materials such as colloidal quantum dots and 2D heterostructures<sup>28–30</sup>. Demonstrating a silicon-native SPI system at a longer SWIR wavelength would therefore provide a direct assessment of whether hyperdoped silicon can satisfy the rigorous requirements for practical room-temperature operation using a stable, CMOS-standard platform.

Here, we seek to validate the practical viability of our hyperdoped silicon photodetector for room-temperature SWIR applications by employing computation-based SPI with 1550 nm source as a system-level test platform. We specifically investigate the impact of ultrafast laser heating (ULH), a processing step that has shown significant promise for improving material-

level properties such as crystallinity, sub-bandgap absorption and its thermal stability<sup>31–34</sup>, but has yet to be validated in a functional device architecture. To determine the optimal fabrication route, we perform a comparative study of devices processed with and without ULH using 1550 nm laser characterization as the deciding benchmark. The optimized device is then subjected to a comprehensive suite of photoelectrical, dynamic, and noise characterizations. Finally, we co-optimize the detector biasing conditions and readout electronics, recognizing that system-level performance in SPI and related applications depends critically on the interplay between intrinsic device properties and external signal amplification and acquisition. Through this structured approach, we assess the potential of a silicon-native, CMOS-compatible platform for room-temperature SWIR photonics.

### **Room-temperature SPI with hyperdoped silicon photodetector**

**Figure 1a** depicts a recently developed computation-based SPI scheme, here adapted by replacing the detector with our hyperdoped silicon device (See ref<sup>29</sup> and **Supplementary Text 1** for details). In short, the light source illuminates the object, and the transmitted light is re-imaged onto a commercial Digital Micromirror Device (DMD, Vialux DLP7000). The DMD comprises an array of independently addressable micromirrors that can be switched between on and off states, enabling computer-controlled spatial modulation of the reflected light through sequentially applied patterns. For each pattern, the total reflected intensity is recorded by the single-pixel hyperdoped silicon detector, and the image is reconstructed numerically from the known modulation sequence and the corresponding detector signals.

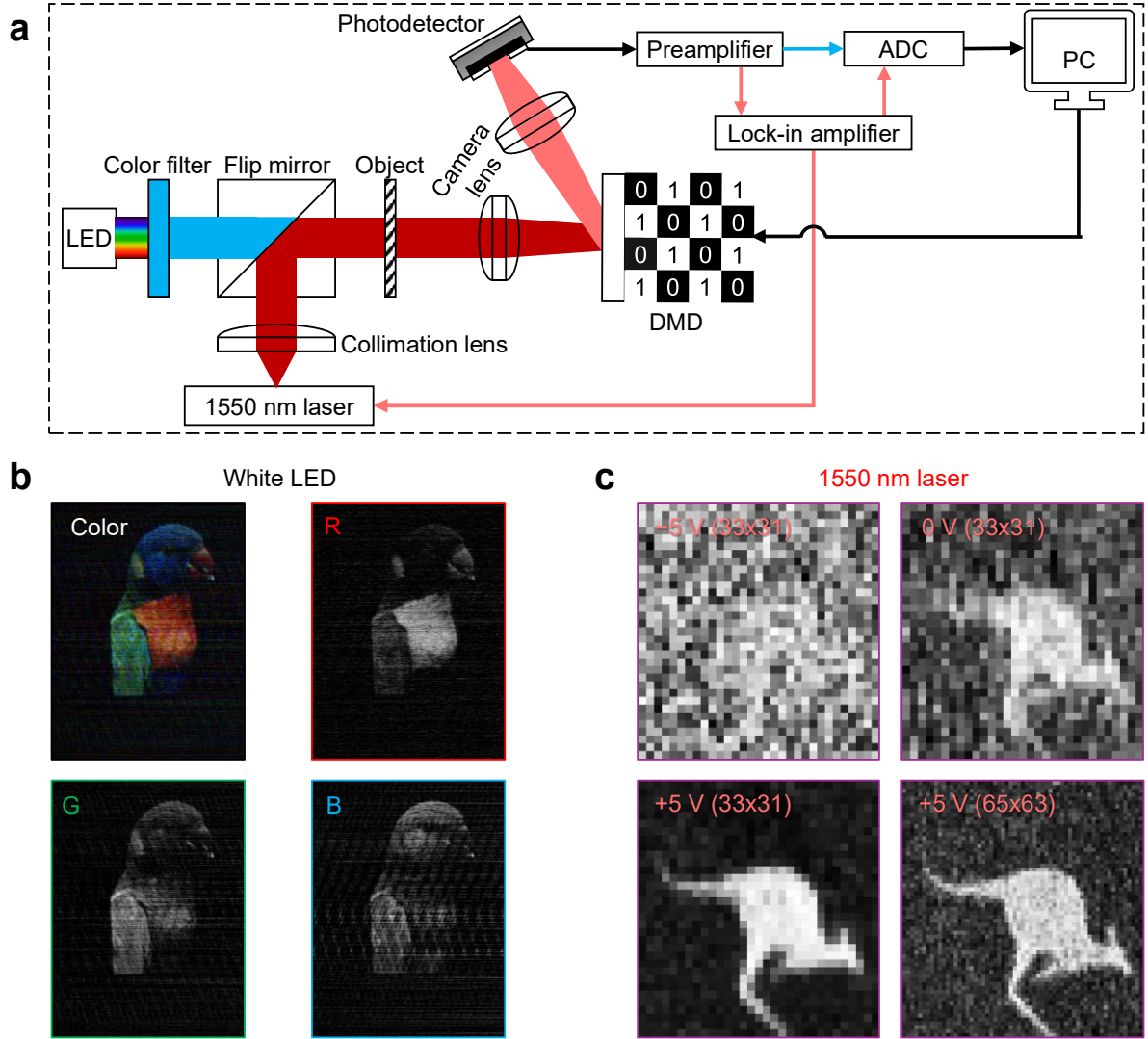


**Figure 1 | Single-pixel imaging (SPI) enabled by a sulfur-hyperdoped silicon photodetector.** **a**, Schematic of the SPI system. The red path indicates the optical and electronic signal route for 1550 nm laser illumination, while the blue path corresponds to broadband LED illumination. The object is spatially modulated by a digital micromirror device (DMD), and the reflected light is collected by a sulfur-hyperdoped silicon photodetector, followed by pre-amplification, lock-in detection (for 1550 nm modulation), analog-to-digital conversion (ADC), and computer-based reconstruction. **b**, Multispectral SPI of a rainbow lorikeet object under white-LED illumination, showing the reconstructed full-color image and the corresponding red (R), green (G), and blue (B) channels with a resolution of  $768 \times 1023$  pixels. **c**, Reconstructed images from a kangaroo shaped object obtained under 1550 nm laser illumination at different bias voltages and spatial resolutions, demonstrating the dependence of image quality on operating conditions.

To first validate the functionality of our hyperdoped silicon detector with the imaging setup, we perform multispectral imaging with a visible light source to leverage the high intrinsic absorption of silicon for an initial optical calibration. A semitransparent rainbow lorikeet target is illuminated with a white-light LED, and red, green and blue filters are sequentially inserted to enable wavelength-selective measurements. Owing to the inherently large above-bandgap response, the signal-to-noise ratio is high enough to ensure no special optimization, except the usual optical path alignment, is required to realize imaging. In this regime, the photocurrent is converted to a voltage by a preamplifier and directly digitized, while spatial

patterns are projected at the DMD's maximum operating frequency ( $\sim 22.7$  kHz). **Figure 1b** shows reconstructed RGB images with  $768 \times 1023$  pixels from an acquisition time of 47 s for each panel, demonstrating that the large-area hyperdoped-Si detector supports high-resolution, high-speed, multispectral SPI when light absorption is not bandgap-limited.

Having established system-level functionality, we next evaluate performance at a SWIR wavelength of 1550 nm; while of course central to telecommunications, where eye safety and fiber/atmospheric transparency are paramount, it serves here as a critical quantitative proxy for the broader SWIR spectrum. In this case, the object is illuminated with a 1550 nm laser, 1.5 kHz intensity-modulated for lock-in detection, and reconstructed from sequential patterned measurements. As shown in **Figure. 1c**, we observe the imaging quality is bias-dependent: under reverse bias ( $-5$  V) the object is barely discernible, and at zero bias the reconstruction remains blurred. Surprisingly, a forward bias of  $+5$  V yields a markedly sharper image with  $33 \times 31$  pixels.

Increasing the sampling density to  $65 \times 63$  pixels further improves the reconstruction quality, with the kangaroo image becoming better-defined. The optimized image is reconstructed from 4096 patterns with a total acquisition time of 14 min, suggesting that SWIR SPI can be realized within experimentally practical timescales and indicating the hyperdoped detector satisfies certain bandwidth requirement in sub-bandgap response. With the practical viability of the silicon-based SWIR imager demonstrated, we next focus on fundamentally understanding how it works, systematically linking the macro-scale imaging performance back to its micro-scale material fabrication and localized electronic transport.

## Device fabrication and electrical–optical characteristics

**Figure 2a** shows the process flow for the fabrication of hyperdoped silicon detectors. As our lightly doped p-type substrate is hyperdoped with sulfur, nominally generating a heavily doped  $n^+$  type region<sup>33</sup>, the final device architecture (**Figs. 2b and 2c**) incorporates dual-mode geometry: a vertical configuration (i.e., front-to-back contacts) for primary operation in nominal photodiode mode and a lateral configuration (i.e., front-to-front contacts) for photoconductor mode as well as for verifying the establishment of the ohmic contacts.

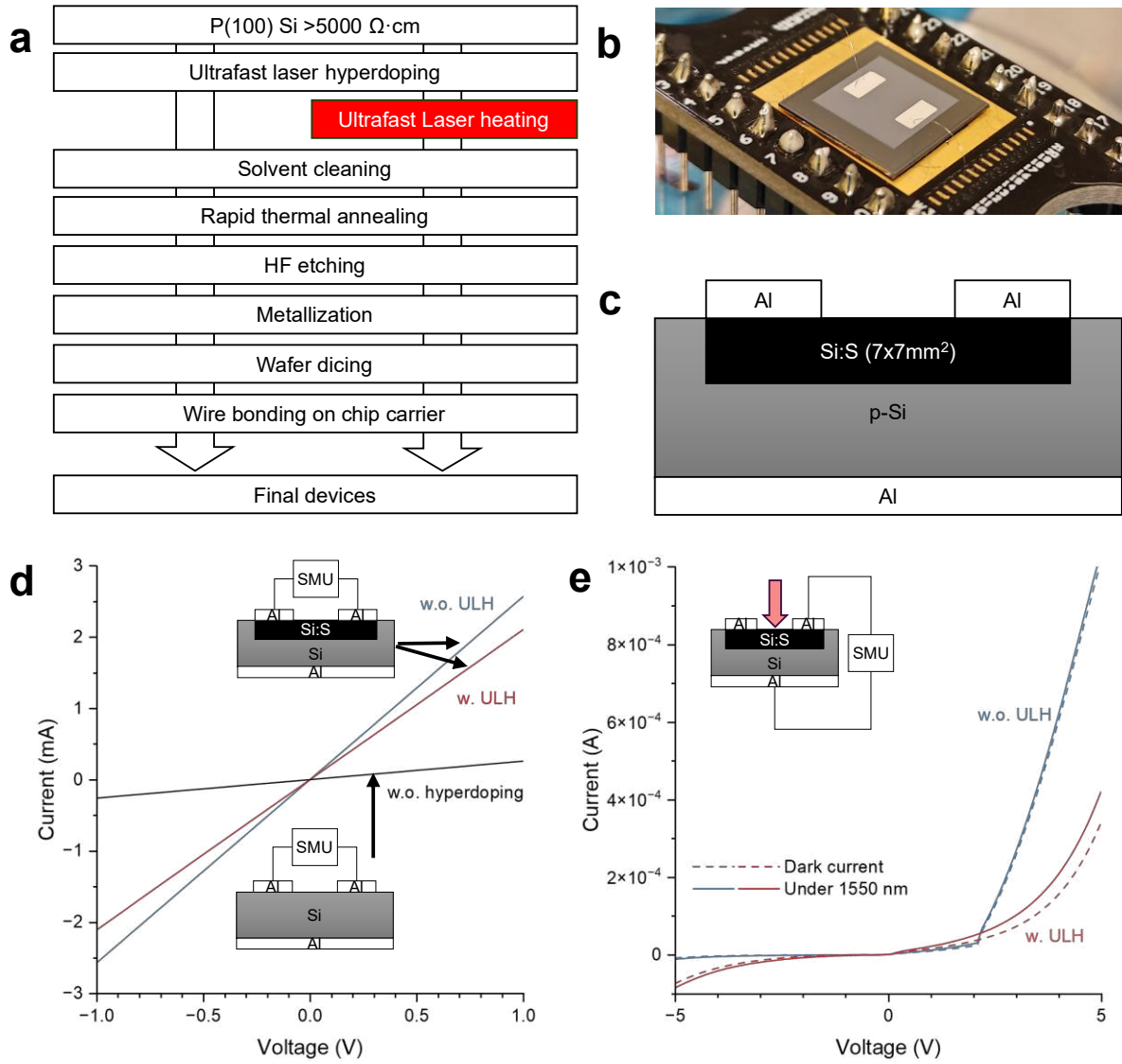


**Figure 2 | Fabrication process, device architecture, and electrical-optical characteristics of the sulfur-hyperdoped silicon photodetectors.** **a**, Process flow for device fabrication on high-resistivity p-type Si, including ultrafast-laser sulfur hyperdoping with optional ultrafast laser heating (ULH). **b**, Photograph of a representative packaged device mounted on a chip carrier and prepared for electrical characterization. **c**, Schematic cross-section of the photodetector with nominal  $n^+$  type Si:S layer. **d**, Representative current-voltage (I-V) characteristics under dark measured between front-front contacts. **e**, Dark and light (1550 nm, 4.88 mW) illuminated I-V curves for devices fabricated with and without ULH. Inset shows a schematic of the measurement between front-rear contacts.

Initially, we fabricated a series of detectors with systematically varied laser fluence and scan speed during ultrafast laser hyperdoping and introduced an additional ULH step (Fig.2a) for a subset of samples to assess its impact at the device level. To strictly isolate the influence of the ULH treatment on device performance, our analysis focuses on a representative pair of detectors showing sub-bandgap response in vertical mode (Supplementary Text 2). Both devices were processed under completely identical hyperdoping conditions, with the ULH step serving as the single experimental variable.

Following wafer dicing and packaging, we verified the contact behavior via lateral I-V measurements using a source measurement unit (SMU). Figure 2d shows that all samples

including ULH-treated, a non-ULH, and an additional pristine-Si reference (to verify the back contact) exhibit linear, ohmic characteristics. Notably, the ULH-treated sample displays a reduced I–V slope relative to the non-ULH counterpart, originating from an increase in sheet resistance or a decrease in sheet carrier density following the ULH, in line with previous material study<sup>33,35</sup>.

Having established the sub-bandgap activation, we next address the highly unconventional bias dependence observed during the SPI experiment (**Fig. 1c**). Given that the optimal imaging performance occurs under forward bias, a behavior entirely unexpected for a standard p–n junction, a further investigation into the bias-tunable transport mechanisms is essential. Therefore, we characterized the I–V response in the dark and under 1550 nm illumination (**Fig.2e**).

The measured curves exhibit weak rectification consistent with the formation of a laser-induced p–n junction. Notably, the ULH-treated device shows a slight reduction in rectification compared to the non-ULH counterpart, characterized by a marginally lower forward dark current, consistent with horizontal mode (**Fig.2d**), along with a higher reverse dark current. The reduction in (forward) dark current under both modes suggests that the ULH step modifies the effective junction properties, potentially through a redistribution of active dopants or a change in the trap-assisted transport mechanisms that govern sub-bandgap carrier collection. Interestingly, under 1550 nm illumination, the non-ULH device exhibits a marginal change in current, while the ULH-treated device shows a pronounced photocurrent response, particularly under forward bias.

Crucially, the higher photocurrent at +5V bias aligns with our experimental observations from the sub-bandgap SPI demonstration on the same ULH-treated device, where this bias yielded the highest reconstruction fidelity and contrast. Previous studies<sup>31–33,36</sup> indicate that millisecond-scale ULH processing can, on the one hand, preserve or reactivate sub-bandgap absorption by driving sulfur dopants into optically active configurations that remain stable under subsequent thermal treatment. On the other hand, ULH also suppresses dark-current-related noise by improving crystallinity and reducing leakage pathways in the hyperdoped region (See **Supplementary Text 3** for detailed discussion). Accordingly, the sub-bandgap imaging performance and increased photocurrent we observe demonstrate that ULH provides a practical defect-engineering strategy for silicon-native SWIR photodetectors, enabling an optimized trade-off between sub-bandgap absorption and dark current noise under forward bias.

However, these SMU-based measurements have inherent limitations. As the bias voltage increases and the dark current grows, the large DC background forces the SMU into a high-current range where the sub-bandgap photocurrent approaches the measurement uncertainty, particularly when the optical excitation is weak (e.g., reduced laser intensity or lamp–grating sources). This issue can be further escalated by unshielded, random ambient light that effectively adds to the dark current (**Supplementary Text 4**). Consequently, the historically modest performance reported for hyperdoped silicon devices at longer SWIR wavelengths may largely reflect these measurement bottlenecks and the use of non-optimized front-end

readout circuits, rather than intrinsic material limits. This motivates a comprehensive dynamic (laser-modulated) characterization and co-optimization of the readout electronics to accurately extract the intrinsic performance of the ULH-treated device and thereby realize the detector's full potential.

### Room-temperature 1550-nm dynamic photoresponse

As demonstrated in our SPI system, the low-noise current preamplifier is a fundamental prerequisite for converting the photocurrent into an ADC-readable voltage signal, allowing us to access the high-quality image with 1550 nm from the detector. As visualized in **Figure 3a**, the preamplifier provides a tunable bias (up to  $\pm 5$  V) and adjustable transimpedance gain (reciprocal to sensitivity), and together with the laser modulation reference, the output voltage is recorded and translated to photocurrent using the known gain. To prevent the large bias-induced dark current from overloading the readout electronics, a DC offset must be applied so that the weaker transient photocurrent can be accurately amplified and resolved.

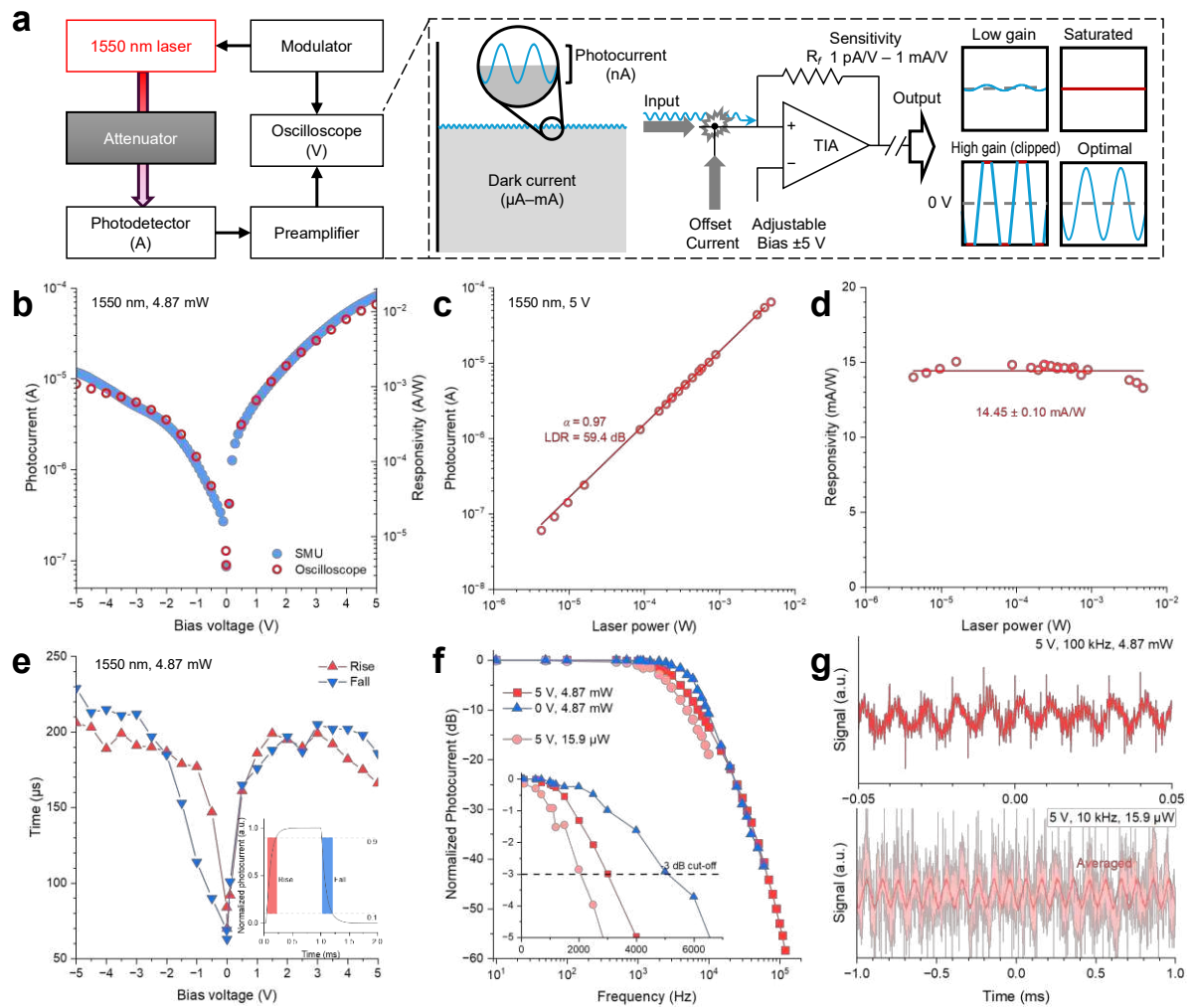


**Figure 3 | Dynamic electrical-optical characterization of the sulfur-hyperdoped silicon photodetector at 1550 nm. a.** Measurement setup for 1550-nm dynamic characterization. Inset schematic shows the photocurrent is amplified by a low-noise transimpedance amplifier (TIA) with adjustable sensitivity and bias, followed by signal and output amplification and

oscilloscope readout. All measurements are performed under vertical mode. **b**, Bias-dependent photocurrent and responsivity measured under 1550-nm illumination (4.87 mW) with a comparison of data collected from IV (under continuous illumination) and TIA + oscilloscope (light modulated at 500 Hz). **c**, Photocurrent as a function of incident laser power at 5 V bias, exhibiting linear behavior over nearly three orders of magnitude and yielding a linear dynamic range (LDR) of 59.4 dB. **d**, Extracted responsivity versus optical power, showing a nearly constant average value of 14.5 mA W<sup>-1</sup> at 1550 nm. **e**, Rise and fall times as a function of bias voltage measured at 1550 nm (4.87 mW), with representative transient traces (at 5 V) shown in the inset. **f**, Frequency-dependent normalized photocurrent at different bias voltages and optical powers, indicating -3 dB cutoff frequencies in the kHz range. **g**, Time-domain photocurrent signals recorded at 5 V under high-frequency modulation (100 kHz, 4.87 mW) and low-power operation (10 kHz, 15.9 μW), with averaged traces highlighting stable periodic response.

**Figure 3b** shows the photocurrent obtained from our SPI-ready preamplifier setup matches the steady-state results derived from SMU measurements ( $I_{1550\text{ nm}} - I_{\text{dark}}$  in **Fig. 2e**) over  $\pm 5$  V bias range. The divergence observed at larger biases is likely due to thermal effects; specifically, continuous illumination during SMU sweeps can trigger self-heating, resulting in an artificially inflated conductive change that is absent during transient, modulated operation. Note these comparisons were performed at maximum available laser intensity to ensure the photocurrent remained within the detectable range of the SMU. However, at the lower power densities typical of SWIR sensing and imaging, the SMU would fail in accurate measurement and thus an optimized preamplifier setup could allow high-fidelity signal extraction even when the photocurrent is several orders of magnitude weaker than dark current.

Importantly, the photocurrent is systematically larger under forward bias than under reverse bias, mirroring the behavior of the dark current in **Fig. 2e**. This indicates predominantly photoconductive operation at 1550 nm rather than efficient photovoltaic junction behavior. This forward-biased optimum is consistent with several reports on hyperdoped-Si photodetectors with similar vertical architecture, but contrasts with most other studies where reverse bias yields the best performance (**Supplementary Table 1**). These discrepancies suggest that the optimal operating polarity is highly sensitive to the detailed junction configuration and defect distribution in the hyperdoped region, which cannot be treated as an ideal photodiode or photoconductor.

For sub-bandgap detection, a high dopant density near the surface is essential to enable sufficient absorption and carrier generation<sup>18,19</sup>. However, in our structure the hyperdoped region confined near the surface, while the depletion region of the nominal p-n junction primarily extends into the lightly doped substrate. Consequently, photocarriers generated within the hyperdoped layer lie largely outside the space-charge region and therefore do not directly benefit from the enhanced carrier separation typically provided by reverse bias. For simplicity, the device can thus be viewed as a hyperdoped conductive layer electrically in series or partially overlapped with a relatively weak rectifying junction<sup>33</sup>, although a comprehensive theoretical treatment of these sub-bandgap carrier dynamics is beyond the scope of this demonstration and warrants dedicated future study. Under forward bias, the junction field is partially reduced, and carrier transport within the hyperdoped region becomes dominant, leading to behavior more characteristic of a photoconductive mode in vertical direction rather than conventional depletion-region photodiode operation. Under +5 V bias, the detector achieves an apparent linear dynamic range of 59.4 dB (**Fig. 3c** and

**Supplementary Text 5)** corroborated by an average responsivity of  $R \approx 14.5 \text{ mA W}^{-1}$  at 1550 nm (**Fig. 3d**).

Detector dynamics are critical for SPI where the modulation rate sets the achievable imaging speed. Under 1550 nm modulation, both rise and fall times are longer under bias than at 0 V (**Fig. 3e**). These quantities are extracted from the averaged temporal traces as exemplified in **inset of Fig. 3e**. Prior reports on hyperdoped silicon photodetectors with similar architectures highlight the role of defect-related trapping centers in governing photoconductive gain mechanism<sup>18,19,24</sup>, which increases the responsivity but lowers the response speed. Here we further clarify that the bias-activated gain should originate primarily from an imbalance between mobile majority and minority carriers within the conduction channel<sup>37</sup>. Upon illumination, photogenerated minority carriers are preferentially localized by defect and surface-related trap states, while their majority counterparts remain mobile and accumulate in the conductive hyperdoped layer. This imbalance enhances channel conductivity and results in an apparent photoconductive gain. Thus, the device transits from a photodiode mode to a photoconductive mode under forward bias. Increasing the bias could modify the apparent minority carrier lifetime presumably by altering carrier confinement, trap occupation, and the local electric-field distribution, thereby tuning both the magnitude of the gain and the detector dynamics.

Forward bias at +5 V offers a favorable compromise between photoconductive gain and speed and is therefore preferred for high-speed imaging. This is in contrast with previous studies showing higher photocurrent gain with the expense of milliseconds response time<sup>24,27,38</sup>. The modulation bandwidth, obtained from the photocurrent as a function of modulation frequency (**Fig. 3f** and **Supplementary Text 6**), yields  $-3 \text{ dB}$  cutoff frequencies  $f_c$  of  $\sim 5 \text{ kHz}$  at 0 V and  $\sim 3 \text{ kHz}$  at +5 V under 4.87 mW illumination, in reasonable agreement with the values inferred from the temporal response ( $\sim 5 \text{ kHz}$  and  $\sim 2.1 \text{ kHz}$ , respectively; **Supplementary Text 7**).

For SPI operation, the optical power incident on the detector is substantially reduced by object attenuation, DMD modulation and relay-optic losses<sup>29</sup>. Analogously, at a substantially reduced incident power of  $15.9 \text{ }\mu\text{W}$  and +5 V bias, the  $f_c$  decreases to  $\sim 2 \text{ kHz}$  (**Fig. 3f**), but remains on the same order of magnitude, indicating only weak dependence of the temporal response on illumination in the relevant range.

The  $-3 \text{ dB}$  frequency does not represent a hard operating limit: modulated signals remain resolvable well above  $f_c$  (**Fig. 3g**). Under strong illumination, a clear periodic response is observed up to 100 kHz, where the preamplifier bandwidth becomes limiting, and at low power the signal remains visible at 10 kHz with temporal averaging. Thus, under realistic SPI conditions, the device supports modulation rates comfortably within the kHz regime with headroom for operation at higher frequencies via device and optical engineering.

### **Readout co-optimization and noise-limited detectivity**

Since practical operation is determined by signal-to-noise rather than responsivity alone, to enable a fair comparison of device performance under realistic operating conditions, we

extract the specific detectivity  $D^*$  as a practical figure of merit<sup>39,40</sup>. To ensure a scientifically valid measurement of  $D^*$ , it is critical that the photocurrent and the noise spectral density are characterized under the same conditions.

**Figure 4a** plots the output voltage as a function of preamplifier sensitivity  $S$  for high (4.87 mW) and low (15.9  $\mu$ W) incident powers. In the high sensitivity regime, reducing  $S$  leads to a linear increase in output voltage while the inferred photocurrent, i.e., amplitude  $\times$  sensitivity, remains essentially unchanged. At smaller  $S$ , the response becomes power-dependent. At  $S < 20 \mu\text{A V}^{-1}$ , the output under 4.87 mW illumination overloads, indicating that the preamplifier input or output stage has reached its dynamic range limit. Under 15.9  $\mu$ W illumination, the response begins to deviate from linear trend in this regime ( $S < 20 \mu\text{A V}^{-1}$ ). This is because the effective bandwidth decreases at higher gain, so the actual gain at the 500 Hz modulation frequency starts to be lower than the nominal value.

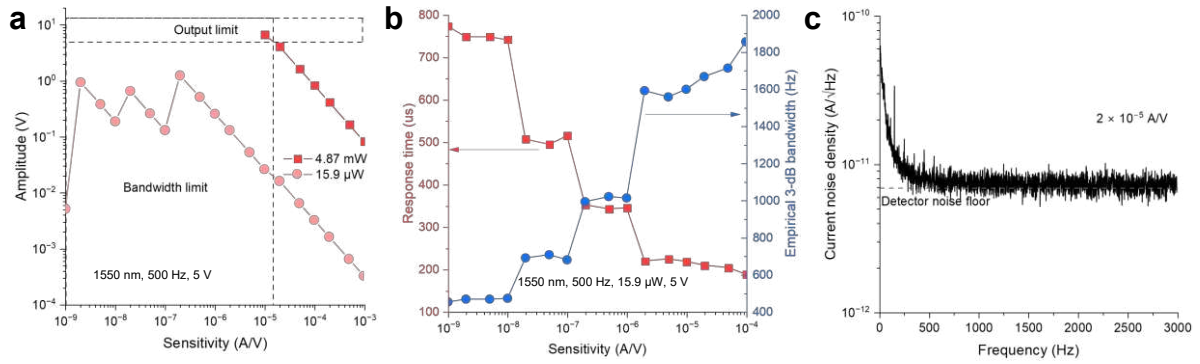


**Figure 4 | Preamplifier optimization and noise analysis of the sulfur-hyperdoped silicon photodetector.** **a**, Measured voltage amplitude at the amplifier output as a function of transimpedance-amplifier sensitivity for two incident optical powers (4.87 mW and 15.9  $\mu$ W at 1550 nm) at a bias of 5 V. **b**, Extracted temporal response time (left axis, averaged rise and fall times) and nominal bandwidth (right axis) as a function of amplifier sensitivity at 1550 nm and 5 V bias. **c**, Spectral current noise density measured at sensitivity of  $2 \times 10^{-5} \text{ A V}^{-1}$  with the estimated shot and thermal noise limit at 5 V calculated from dark I–V measurement.

In addition, the impact of  $S$  on detection speed is quantified by extracting the response time as a function of  $S$  under low-power illumination, since high-power operation saturates at large gains and does not provide reliable timing information. **Figure 4b** shows that as  $S$  decreases, the response time increases with corresponding step-like changes from discrete internal gain ranges of the preamplifier, and the effective cutoff frequency  $f_c$  drops from the kHz range at low gain to the sub-kHz range at the highest gains. This suggests that an intermediate gain is required to amplify the photocurrent with little input-referred noise, to avoid overload and to preserve the bandwidth, thereby realizing the practical functionality of the hyperdoped silicon detector in SWIR applications.

We next characterize the noise of the detector–preamplifier system using FFT-based current-noise spectra (see **Supplementary Text 8** for details). **Figure 4c** shows the current-noise spectral density  $i_n(f)$  at the sensitivity  $S = 20 \mu\text{A V}^{-1}$  and bias of +5 V, together with the shot and thermal noise floor estimated from dark I–V curve (**Supplementary Text 9**). At low frequencies, the spectrum exhibits a pronounced  $1/f$ -like slope and possibly mixed with trap-related generation–recombination noise, while in the 500–3000 Hz range it flattens

into a white-noise plateau that approaches the detector noise floor, dominated by the shot noise from relatively large dark current. For practical operation, the laser modulation frequency should therefore be chosen above the  $1/f$ -dominated region, where the noise is close to the white-noise limit that is dominated by the shot noise.

The specific detectivity  $D^*$  is extracted from the measured photocurrent (**Fig. 4a**) and the average white noise  $\bar{i}_n$  over 500–3000 Hz (**Fig. 4c**). Under a +5 V bias and 1550 nm illumination, we obtain  $D^* \approx (1.91 \pm 0.18) \times 10^9$  Jones (or  $\text{cm Hz}^{1/2} \text{W}^{-1}$ ) for 15.9  $\mu\text{W}$  and  $D^* \approx (1.59 \pm 0.16) \times 10^9$  Jones for 4.87 mW. These values lie near the upper bound of reported performance for silicon-native photodetectors at 1550 nm without heterojunction integration (**Supplementary Table 1 and Ref<sup>26</sup>**). By contrast,  $D^*$  estimated at 0 V and –5 V is  $3.26 \times 10^8$  and  $3.33 \times 10^8$  Jones, respectively, using the photocurrent in **Fig. 3b** and dark I–V inferred noise floor. The highest detectivity at +5 V bias is consistent with the best image quality achieved at this forward-bias operating point.

## Conclusion

These results represent the first demonstration of room-temperature SWIR computational imaging using silicon-native architecture. The large-area sulfur-hyperdoped silicon detector, engineered by ultrafast laser processing with a ULH step, delivers responsivity of  $\sim 14.5 \text{ mA W}^{-1}$ , specific detectivities above  $10^9$  Jones, a linear dynamic range of  $\sim 59$  dB and kHz-scale bandwidth, with ULH improving the photocurrent while suppressing the dark current resulting in a forward bias, photoconductive-like operation mode. As a proxy for the broader SWIR applications, we show the hyperdoped-silicon integrated SPI architecture enables object reconstruction at 1550 nm in addition to high-resolution multispectral (RGB) imaging, demonstrating that a single silicon-based pixel can tackle broadband visible to SWIR imaging. The detector-limited noise behavior we observe under matched readout suggests that hyperdoped silicon's SWIR performance has been systematically understated by conventional characterization. Further advances in defect engineering, device design and readout co-optimization could extend silicon's usefulness deeper into the SWIR for telecom, sensing and imaging applications.

## Materials and methods

### *Device fabrication and screening*

The hyperdoped silicon photodetector was fabricated on a 280- $\mu\text{m}$  thick, double-side-polished, p-type, 4" float-zone (100) silicon wafer with a resistivity of  $5000 \pm 3000 \Omega \cdot \text{cm}$ . The wafer was first irradiated with ultrashort laser pulses in 675 mbar sulfur hexafluoride atmosphere. The Yb:YAG laser source (Amplitude Tangor 100) emitted pulses at the central wavelength 1030 nm with 10 ps pulse duration at an adjustable repetition rate of 200 kHz to 41 MHz. The output pulse energy of the laser source was controlled with an acousto-optical modulator. The laser pulses passed through a scanning system consisting of a two-axis

galvanometer scanner and a  $f$ -theta lens with a focal length of 340 mm and were focused onto the wafer surface inside the processing chamber. The  $1/e^2$  beam diameter was measured with a camera-based beam profiling system in the focal plane to be  $2w_0 = 70\ \mu\text{m}$ . The pulses were scanned across the wafer surface in a square-shaped grid pattern with a size of  $7\ \text{mm} \times 7\ \text{mm}$  with a period of  $1\ \text{cm} \times 1\ \text{cm}$ . Hyperdoping was performed using 500 pulses per area with a peak fluence of  $1.2\ \text{J cm}^{-2}$ . Subsequently, ULH was applied to selected samples in ambient air using a repetition rate of 41 MHz, a scanning speed of  $3000\ \text{mm s}^{-1}$ , and a peak fluence of  $10\ \text{mJ cm}^{-2}$ . These processing parameters were optimized for the devices used in the SPI demonstration; additional variations are documented in **Supplementary Text 2**.

After laser processing, the wafer was subsequently cleaned in ultrasonically agitated acetone and isopropyl alcohol and then rinsed in de-ionized water to remove the dust residues. We then performed rapid thermal annealing (RTA) at  $900\ ^\circ\text{C}$  for 10 s in an  $\text{N}_2$  ambient. The wafer was then etched in 1% hydrofluoric acid (HF) for 1–2 min to remove native oxides. Immediately after HF etching, metallization was carried out via e-beam evaporation (Angstrom Engineering, model 09340) of 500 nm Al on both sides of the wafer. The front side was patterned using a 304 stainless steel shadow mask, while the back side received a full-area Al layer. The resulting front-side contacts measured  $1.5\ \text{mm} \times 3\ \text{mm}$  and were spaced by 3 mm.

To verify Ohmic contact behavior, the devices were measured between two adjacent front contacts using a semiconductor parameter analyzer (Keysight/Agilent 4156A). To confirm Ohmic behavior on the back planar side, a reference sample with two pads on the non-hyperdoped, pristine area was also fabricated and characterized.

After initial testing of sub-bandgap responsivity, the wafer was diced into  $1\ \text{cm} \times 1\ \text{cm}$  devices using a UV laser (LPKF U4) and selected devices were then individually bonded onto custom chip carriers for device characterization and imaging experiments. To compare devices with and without the ULH step, each chip was mounted in a light-shielded enclosure, and I–V characteristics were measured by a SMU (Keysight 2450) under dark conditions and under continuous 1550 nm laser illumination, with a maximum intensity of 4.87 mW calibrated by a Ge photodiode (Thorlabs FDG03).

### ***Photocurrent characterization under laser illumination***

For 1550-nm laser characterization, the device was mounted in the same light-shielded enclosure and illuminated with a 1550 nm laser diode (LD) whose intensity was calibrated by the same Ge photodiode. The LD was driven by a current controller (Thorlabs LDC205C) and modulated by a function generator (Stanford Research DS345) using a square-wave signal at selected frequencies. The device output was pre-amplified with a low-noise current amplifier (Stanford Research SR570) and converted to a voltage signal, which was then recorded with an oscilloscope (Tektronix MSO2024B). A set of neutral density (ND) filters was used to attenuate the laser intensity, enabling measurement of laser-power-dependent photocurrent for linear dynamic range analysis and low-light characterization.

By adjusting the preamplifier sensitivity  $S$ , we effectively tuned the transimpedance gain and determined the input current  $I_{\text{in}}$  from the measured oscilloscope voltage using the known current-to-voltage gain:

$$I_{\text{in}} = V_{\text{out}} \cdot S = \frac{V_{\text{out}}}{G},$$

where  $V_{\text{out}}$  is the recorded preamplifier output voltage and  $G$  is the transimpedance gain.

## References

- 1 van den Hout M, S. Luís R, Puttnam BJ, Di Sciullo G, Hayashi T, Inoue A *et al.* Reaching the pinnacle of high-capacity optical transmission using a standard cladding diameter coupled-core multi-core fiber. *Nat Commun* 2025; **16**: 3833.
- 2 Shekhar S, Bogaerts W, Chrostowski L, Bowers JE, Hochberg M, Soref R *et al.* Roadmapping the next generation of silicon photonics. *Nat Commun* 2024; **15**: 751.
- 3 Petrovich M, Numkam Fokoua E, Chen Y, Sakr H, Adamu AI, Hassan R *et al.* Broadband optical fibre with an attenuation lower than 0.1 decibel per kilometre. *Nat Photonics* 2025; **19**: 1203–1208.
- 4 Zhang X, Kwon K, Henriksson J, Luo J, Wu MC. A large-scale microelectromechanical-systems-based silicon photonics LiDAR. *Nature* 2022; **603**: 253–258.
- 5 Yamazaki S, Tamanuki T, Ito H, Kubota R, Baba T. Silicon FMCW LiDAR chip integrated with SLG beam scanner and k-clock interferometer for operation with wavelength-swept laser source. *Opt Express* 2024; **32**: 21191.
- 6 Lukashchuk A, Yildirim HK, Bancora A, Lihachev G, Liu Y, Qiu Z *et al.* Photonic-electronic integrated circuit-based coherent LiDAR engine. *Nat Commun* 2024; **15**: 3134.
- 7 McCarthy A, Taylor GG, Garcia-Armenta J, Korzh B, Morozov D V., Beyer AD *et al.* High-resolution long-distance depth imaging LiDAR with ultra-low timing jitter superconducting nanowire single-photon detectors. *Optica* 2025; **12**: 168.
- 8 Juan-Colás J, Parkin A, Dunn KE, Scullion MG, Krauss TF, Johnson SD. The electrophotonic silicon biosensor. *Nat Commun* 2016; **7**: 12769.
- 9 Oh S-H, Altug H, Jin X, Low T, Koester SJ, Ivanov AP *et al.* Nanophotonic biosensors harnessing van der Waals materials. *Nat Commun* 2021; **12**: 3824.
- 10 Bryan MR, Butt JN, Bucukovski J, Miller BL. Biosensing with Silicon Nitride Microring Resonators Integrated with an On-Chip Filter Bank Spectrometer. *ACS Sens* 2023; **8**: 739–747.

- 11 Grünenfelder F, Boaron A, Resta G V., Perrenoud M, Rusca D, Barreiro C *et al.* Fast single-photon detectors and real-time key distillation enable high secret-key-rate quantum key distribution systems. *Nat Photonics* 2023; **17**: 422–426.
- 12 Walsh SM, Karpathakis SFE, McCann AS, Dix-Matthews BP, Frost AM, Gozzard DR *et al.* Demonstration of 100 Gbps coherent free-space optical communications at LEO tracking rates. *Sci Rep* 2022; **12**: 18345.
- 13 Inoue T, Morita R, Ishimura S, Nakano S, Takahashi H, Tsuritani T *et al.* Frequency-modulated high-power photonic-crystal surface-emitting lasers for long-distance coherent free-space optical communications. *Nat Photonics* 2025; **19**: 1330–1335.
- 14 Zhang J, Shao R, Xu H, Tan KH, Wicaksono S, Kong Q *et al.* Flexible InGaAs/InAlAs avalanche photodiodes for short-wave infrared detection. *Nat Commun* 2025; **16**: 9367.
- 15 Mouloua D, Martin M, Ilahi B, Cavalaglio S, Chauvin N, Bassani F *et al.* Scalable InAs/InGaAs DWELL structures for broadband infrared emission spanning the E- to O-band. *Sci Rep* 2025; **15**: 37470.
- 16 Tang Y, Wang R, Yang X, He T, Liu Y, Zhao M. High crosstalk suppression in InGaAs/InP single-photon avalanche diode arrays by carrier extraction structure. *Nat Commun* 2024; **15**: 593.
- 17 Mailoa JP, Akey AJ, Simmons CB, Hutchinson D, Mathews J, Sullivan JT *et al.* Room-temperature sub-band gap optoelectronic response of hyperdoped silicon. *Nat Commun* 2014; **5**: 3011.
- 18 Sher M-J, Hemme EG. Hyperdoped silicon materials: from basic materials properties to sub-bandgap infrared photodetectors. *Semicond Sci Technol* 2023; **38**: 033001.
- 19 Tong Z, Bu M, Zhang Y, Yang D, Pi X. Hyperdoped silicon: Processing, properties, and devices. *Journal of Semiconductors* 2022; **43**: 093101.
- 20 Berencén Y, Prucnal S, Liu F, Skorupa I, Hübner R, Rebohle L *et al.* Room-temperature short-wavelength infrared Si photodetector. *Sci Rep* 2017; **7**: 43688.
- 21 García-Hemme E, García-Hernansanz R, Olea J, Pastor D, del Prado A, Mártil I *et al.* Room-temperature operation of a titanium supersaturated silicon-based infrared photodetector. *Appl Phys Lett* 2014; **104**: 211105.
- 22 Li C, Zhao J-H, Liu X-H, Ren Z-Y, Yang Y, Chen Z-G *et al.* Record-Breaking-High-Responsivity Silicon Photodetector at Infrared 1.31 and 1.55  $\mu\text{m}$  by Argon Doping Technique. *IEEE Trans Electron Devices* 2023; **70**: 2364–2369.

- 23 Zhao X, Lin K, Gao S, Liu H, He J, Wang X *et al.* Efficient Er/O Doped Silicon Photodiodes at Communication Wavelengths by Deep Cooling. *Adv Mater Technol* 2021; **6**: 2100137.
- 24 Huang S, Wu Q, Jia Z, Jin X, Fu X, Huang H *et al.* Black Silicon Photodetector with Excellent Comprehensive Properties by Rapid Thermal Annealing and Hydrogenated Surface Passivation. *Adv Opt Mater* 2020; **8**: 1901808.
- 25 Zhang K, He J, He T, Li Q, Peng M, Guo J *et al.* Extended infrared responses in Er/O-hyperdoped Si at room temperature. *Opt Lett* 2021; **46**: 5165.
- 26 Yang X, Xiong Z, Yu H, Zhang X, Gou J, Zeng G *et al.* Recent Advances in Si-Based Photodiodes for 1–14  $\mu\text{m}$  Infrared Detection. *Adv Funct Mater* 2026; : e13499.
- 27 Yu Z, Cong J, Khan A, Hang P, Yang D, Yu X. Direct growth of graphene on hyper-doped silicon to enhance carrier transport for infrared photodetection. *Nanotechnology* 2024; **35**: 115703.
- 28 Meng H, Gao Y, Wang X, Li X, Wang L, Zhao X *et al.* Quantum dot-enabled infrared hyperspectral imaging with single-pixel detection. *Light Sci Appl* 2024; **13**: 121.
- 29 Khaleghi SSM, Chen J, Balendhran S, Corletto A, Wang S, Liu H *et al.* High Pixel Resolution Visible to Extended Shortwave Infrared Single Pixel Imaging with a black Phosphorus-Molybdenum disulfide (bP-MoS<sub>2</sub>) photodiode. 2025.
- 30 Mou S, Stantchev RI, Saxena S, Ou H, Rane S, Pain SL *et al.* All-fibre-coupled terahertz single-pixel imaging for biomedical applications. *Nat Commun* 2026; **17**: 1571.
- 31 Mc Kearney P, Schäfer S, Paulus S, Roser M, Piermaier F, Lebershausen I *et al.* Ultrafast laser heating for controlling the optoelectronic properties of sulfur hyperdoped black silicon. *J Appl Phys* 2023; **133**: 013102.
- 32 Paulus S, Roser M, McKearney P, Will M, Schäfer S, Kontermann S. Classification of different post-hyperdoping treatments for enhanced crystallinity of IR-sensitive femtosecond-laser processed silicon. *Semicond Sci Technol* 2023; **38**: 024002.
- 33 Paulus S, Schäfer S, Mc Kearney P, Niemeyer T, Seibt M, Kontermann S. Defect engineering for improved thermal stability of sulfur hyperdoped silicon. *Mater Sci Semicond Process* 2024; **176**: 108297.
- 34 Liu X, McKearney P, Schäfer S, Radfar B, Berencén Y, Kentsch U *et al.* Impact of post-ion implantation annealing on Se-hyperdoped Ge. *Appl Phys Lett* 2024; **125**: 042102.
- 35 Liu X, Chen K, Radfar B, Mc Kearney P, Paulus S, Schäfer S *et al.* (poster) Contact formation via femtosecond-laser hyperdoping in silicon optoelectronic devices. Joensuu, Finland, 2023<https://research.aalto.fi/en/publications/poster-contact-formation-via-femtosecond-laser-hyperdoping-in-sil/> (accessed 21 Apr2026).

- 36 Schäfer S, Liu X, Mc Kearney P, Paulus S, Radfar B, Vähänissi V *et al.* Effective Carrier Lifetime in Ultrashort Pulse Laser Hyperdoped Silicon: Sulfur Concentration Dependence and Practical Limitations. *physica status solidi (a)* 2024; **221**: 2400132.
- 37 Dan Y, Zhao X, Chen K, Mesli A. A Photoconductor Intrinsically Has No Gain. *ACS Photonics* 2018; **5**: 4111–4116.
- 38 Li P, Zhang X, Chen S, Yu L, Feng S. Investigation of Ti-DLC film for the near infrared photodetector. *Diam Relat Mater* 2023; **140**: 110478.
- 39 Wang F, Zhang T, Xie R, Wang Z, Hu W. How to characterize figures of merit of two-dimensional photodetectors. *Nat Commun* 2023; **14**: 2224.
- 40 Pecunia V, Anthopoulos TD, Armin A, Bouthinon B, Caironi M, Castellanos-Gomez A *et al.* Guidelines for accurate evaluation of photodetectors based on emerging semiconductor technologies. *Nat Photonics* 2025; **19**: 1178–1188.

## Acknowledgement

X.L. acknowledges financial support from the Research Council of Finland through the Academy Research Fellowship (#354199). S.S. acknowledges funding by the German Federal Ministry of Education and Research in the context of the federal-state program “FH-Personal” under the grant number 03FHP147A (REQUAS). The work is part of the Research Council of Finland Flagship Program, Photonics Research and Innovation (PREIN, #346529). The authors acknowledge the provision of facilities and technical support by Aalto University at OtaNano-Micronova Nanofabrication Centre. We thank Marko Yli-Koski and Rob Delaney for their invaluable technical assistance.

## Author Contributions

Conceptualization: XL, SS, SK, KC, JB, HS; Data curation: XL, JC, PMK, SP; Formal Analysis: XL; Funding acquisition: XL, SS, VV, SK, KC, JB, HS; Investigation: XL, SS, JC, PMK, SP, VAV; Methodology: XL, SS, JC, PMK, SP, KC; Project administration: XL, SS, KC, JB; Resources: XL, SS, VAV, VV, SK, KC, JB, HS; Software: XL, JC, PMK, SP, VAV; Supervision: SK, KC, JB, HS; Validation: XL, SS, VV, SK, KC, JB, HS; Visualization: XL, JC; Writing – original draft: XL; Writing – review & editing: XL, SS, JC, PMK, SP, VAV, VV, SK, KC, JB, HS

## Conflict of interest

The authors declare no competing interests.

## Data availability statements

The authors declare that all datasets on which the conclusions of the paper reply are openly available within the paper, its supplementary information files, and [REPOSITORY].



## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SiSPISupplementaryv5.pdf](#)
- [Datasets.v5.zip](#)