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### **White paper: NRC's photodetector activities in the short-wavelength infrared**

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# White Paper: NRC's Photodetector Activities in the Short-Wavelength Infrared

Non-sensitive

Report No NRC-QN-AEP-056-E

May 12<sup>th</sup> 2025

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NR16-486/2025E-PDF  
ISBN 978-0-660-78046-7

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# White Paper: NRC's Photodetector Activities in the Short-Wavelength Infrared

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## Background

III-V compound semiconductors are the most efficient solid state light emitters and photodetectors. They are the backbone of the laser and detector technologies underpinning optical fibre telecommunications. In addition, for state-of-the-art imaging applications, large area focal plane photodetector arrays (FPAs) in the short-wavelength infrared can be fabricated (SWIR: 1.0-1.7  $\mu\text{m}$  range). These detector technologies are based on the indium phosphide (InP) platform, combined with indium gallium arsenide (InGaAs) for the photon absorber material, and are considered to be the state-of-the-art material system targeting these wavelengths.

The National Research Council of Canada (NRC) and the Canadian Photonics and Fabrication Center (CPFC) have developed extensive capabilities in terms of design, epitaxy, fabrication, and testing of both laser and detector device structures. We are collaborating with other institutions, in Canada and internationally, on further developing these technologies for state-of-the-art performance, and extending our capabilities beyond the SWIR.

## Technology

NRC's photodetector technologies are based on InP/InGaAs epitaxial structures, grown using metalorganic chemical vapour deposition (MOCVD) reactors. They can produce high quality device materials on multiple wafers (2,3,4,6 inch) in each growth run. A key aspect of this technology is the high material, quality which is exemplified by its strong, but also, very uniform photoluminescence signal in terms of peak wavelength (left), and relative photoluminescence magnitude (right) in Figure 1a.

An advanced Zn diffusion process has been developed using CPFC's MOCVD reactors to produce extremely uniform, high quality, reproducible, *p*-type regions into InP. This forms the basis of photodetector pixels with feature sizes as small as 0.4  $\mu\text{m}$ . For example, Figure 1b illustrates Zn diffusion into InP where the large bright region near the surface is Zn-diffused InP

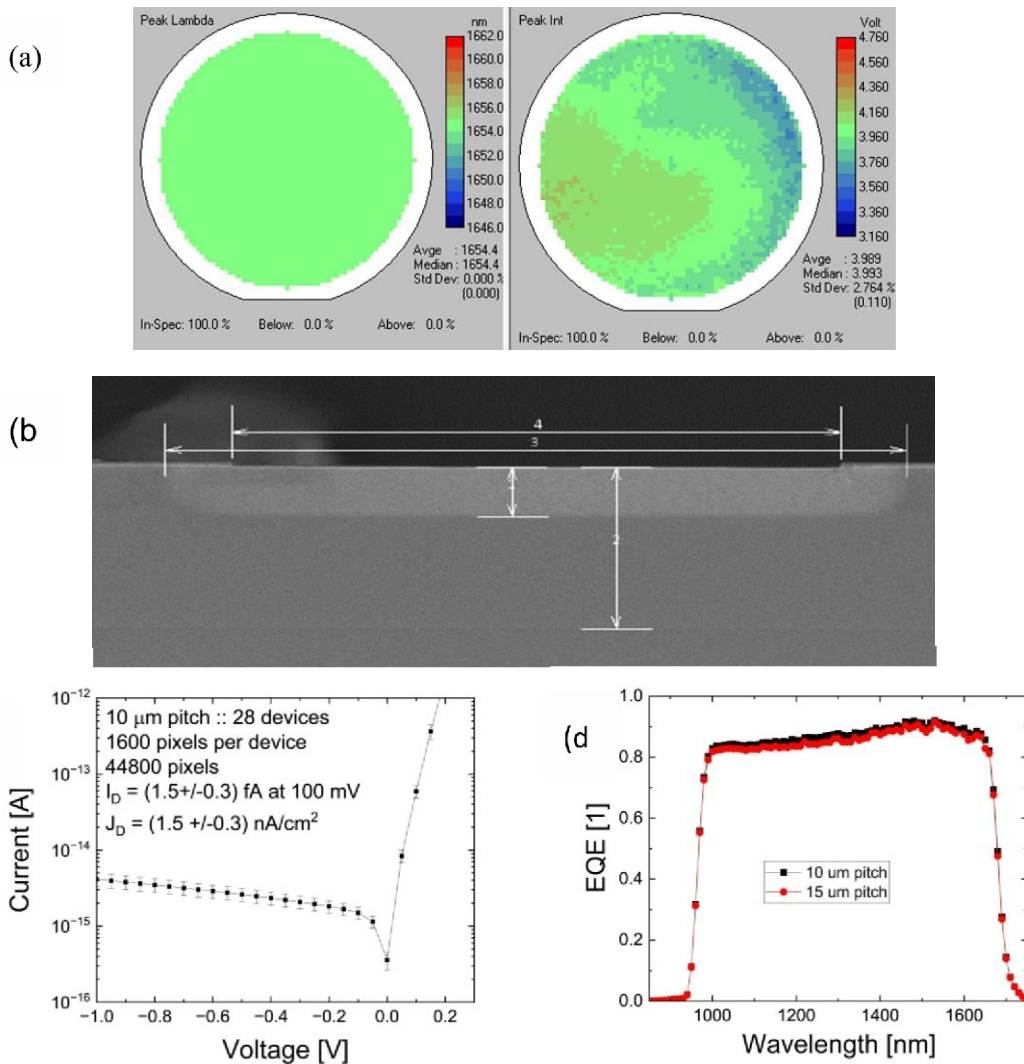


Figure 1. a) Maps of photoluminescence wavelength and relative intensity of an InP/InGaAs wafer outlining its high uniformity and quality, b) scanning electron microscopy image of a cross-section of an InP/InGaAs device highlighting the Zn diffusion process, c) current – voltage data corresponding to 44,800 pixels at room temperature, and d) external quantum efficiency measurements of 10 and 15  $\mu\text{m}$  pitch devices.

targeting a particular target depth. This Zn diffusion process, combined with the high-quality InGaAs, and low noise semiconductor fabrication processing at the CPFC, has demonstrated highly reliable and high-performance pixels down to 10  $\mu\text{m}$  pitch. These have extremely uniform pixel performance, with a dark current density  $<2 \text{ nA/cm}^2$  at room temperature [1] and  $>99\%$  yield. This is illustrated by measurements averaged over 44,800 pixels across the full area of a wafer in Figure 1c. Depositing an optimized anti-reflection coating on the backside of the polished wafer results in  $>80\%$  quantum efficiency, which yields a responsivity  $> 1 \text{ A/W}$  at 1550 nm. Furthermore, test structures on the wafer reveal the minority carrier diffusion lengths, which

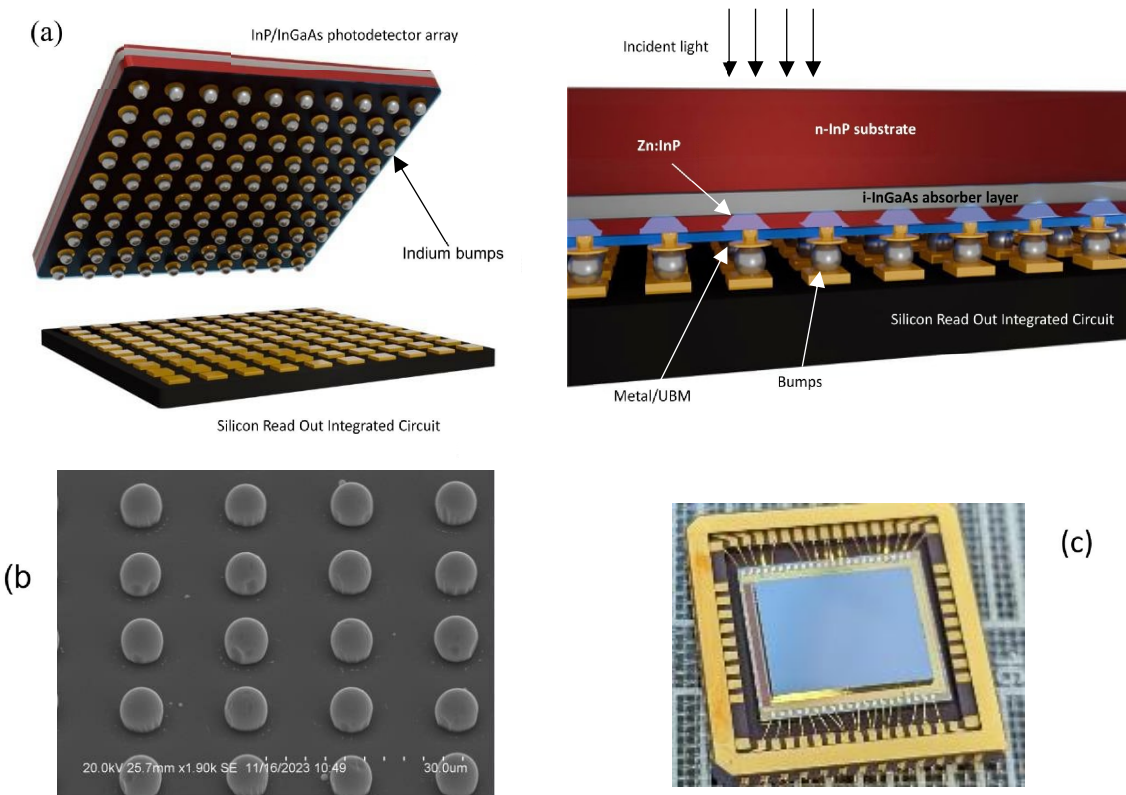


Figure 2. a) Flip chip assembly process schematic, b) indium bumps after reflow prior to flip chip assembly, c) fabricated 640x512 FPA with suitable anti-reflection coating wire bonded to a carrier.

are critical to photodetector performance, with values as high as  $80\ \mu\text{m}$  being reported [2]. These properties reveal the very high quality of NRC's InGaAs materia. These parameters are not often reported in the literature, and show a very stable behavior over temperature between  $0$  and  $100^\circ\text{C}$  [3]. A significant benefit of this Zn diffusion step is in avalanche photodiode (APD) technology development, which has demonstrated strong sensitivity to the diffusion conditions in terms of reactor temperature, Zn concentration and phosphine overpressure [4]. NRC has also developed a selective area growth process to adequately mould the Zn diffusion profile into the epitaxial structure this avoid edge breakdown across the device [6]. A recent finding has shown excellent dark count rates, and photodetector probability results for Geiger-mode operated APDs [7].

NRC has performed extensive research on indium bump as a flip-chip technology to connect millions of pixels from an InP/InGaAs photodetector array (PDA) to a matching read-out integrated circuit (ROIC). Figure 2a illustrates the schematic of this flip chip assembly process, where the light is incident on the backside of the n-doped InP substrate (which is transparent to wavelengths longer than  $920\ \text{nm}$ ). This necessitates high quality indium bumps on each pixel,

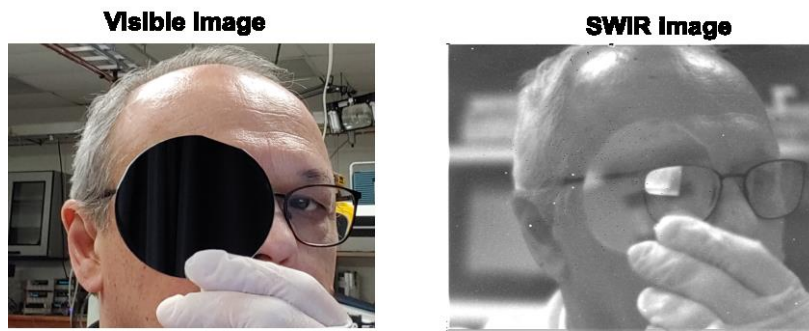


Figure 3. Visible image compared to SWIR image highlighting the transparency of a Si wafer.

where the precise size and height of the indium bumps must be such that each pixel has a high likelihood of resulting in low resistance connectivity, without shorting to neighboring pixels. This is illustrated in Fig. 2b to highlight this uniform behaviour for a 15  $\mu\text{m}$  pitch. Finally, the assembled FPA is then wire bonded to a carrier, as illustrated in Fig. 2c, where the top surface of the InP substrate is coated with a suitable anti-reflection coating to limit reflectivity in the wavelength range of interest.

In collaboration with l'Institut National d'Optique in Quebec, NRC has developed FPA technology with 15  $\mu\text{m}$  pitch, such as the 0.3 mega-pixel (MP) FPA outlined in Figure 2c. We are currently investigating an FPA with 1MP resolution also with a 15  $\mu\text{m}$  pitch. This initiative has led to the generation of high-quality images in the SWIR such as Figure 3 which highlights the transparency of a Si wafer. A good application space for SWIR imaging is in integrated circuit inspection including photovoltaic panels.

## Applications and advantages over existing technologies

### *Imaging in the SWIR*

FPA's operating in the SWIR are capable of producing high quality images with strong resemblance to characteristics typically seen in the visible wavelength range. There are significant advantages of imaging in the SWIR, including night time vision and surveillance, seeing through fog for autonomous driving, seeing through smoke for wildfire monitoring and control, seeing through various plastics for sorting, food production quality control (eg. detecting contaminants in food such as rice, coffee beans, etc. or identifying defects in produce such as bruising or rotting in vegetables/fruits), eye-safe laser range finding, scientific imaging, silicon integrated circuit and photovoltaic panel inspections, even verifying provenance in important artworks by analyzing multiple layers in paintings.

Two particular FPA formats are being developed at the NRC: 640x512 and 1280x1024, the former with >99% operability and low overall read-out noise, the latter currently under

development. However, we can match any formats depending on bespoke ROIC configurations. Pixel fill factors are 100% due to the rear-side illumination of the detector array. Furthermore, for high end applications, NRC has previously developed InP substrate removal capabilities post-FPA assembly to significantly increase the detector’s responsivity to visible wavelengths.

## Custom Designs

Custom InGaAs/InP photodetector configurations can be made available with a dark current density of  $<2 \text{ nA/cm}^2$  at room temperature down to 10  $\mu\text{m}$  pixel pitch and quantum efficiency of  $>80\%$  with a bespoke anti-reflection coating. In principle, NRC has the capabilities of designing pixels down to 1  $\mu\text{m}$ ; however, no read-out circuits are presently commercially available below 10  $\mu\text{m}$  pixel pitch. The specialty of NRC’s technology is the high-end semiconductor epitaxial quality and processing in the CPFC, complemented by years of experience in photodetector design, modeling and characterization. Ultimately, custom epitaxial layers coupled to photodetector array sizes can be designed, fabricated and tested to satisfy a client’s requirements. We are actively investigating novel materials (eg. GaSb-based alloys for extended SWIR detection, or InAs quantum dot-based epitaxial designs for lattice matched extended SWIR detection).

## Example technology specifications

*Table 1. Typical performance specifications for NRC p-i-n based PDAs. Some customization can be done with respect to specifications including pixel pitch, array format, etc.*

Specification	Unit	p-i-n PDA
Pixel pitch	[ $\mu\text{m}$ ]	10, 15
PDA formats	N/A	640x512, 1280x1024
Dark current	[ $\text{nA/cm}^2$ ]	$<3 @ 100 \text{ mV (300K)}$
Responsivity	A/W	$>1 @ 1.55 \mu\text{m}$
Spectral range	[ $\mu\text{m}$ ]	0.9-1.7

## Prototyping and manufacturing

The NRC’s CPFC is North America’s only pure-play foundry for III-V semiconductor optoelectronics. It is located in Ottawa, Ontario, Canada, and offers a range of fabrication services from prototyping, through to full-scale volume manufacturing. The CPFC’s facility is

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equipped with the latest tools and equipment for processing photonic devices and photonic integrated circuits, and offers a range of foundry services:

- Epitaxial growth MOCVD
- Molecular beam epitaxy (MBE)
- Chemical beam epitaxy (CBE)
- Plasma-enhanced vapour phase deposition (PECVD)
- Projection and electron-beam lithography, metallization, plasma etching and back-end processing

NRC also offers the following complementary services:

- Design and modeling:
  - Mask design of bespoke components such as linear arrays, two-dimensional arrays, single devices, quadrant devices, etc.
  - Technology Computer Aided Design (TCAD) of semiconductor optoelectronics for optimization based on calibrated material models for InP, InGaAsP, GaAs, AlGaAs, GaN, etc.
- Test and characterization:
  - Electrical measurements using the Keysight B1500A semiconductor device parameter analyzer with fA resolution, capacitance voltage profiling, pulsed/dynamic IV, etc.
  - Summit Cascade prober for reliable, automated wafer maps to provide uniformity and statistics of final products
  - Optoelectronic characterization based on SWIR and extended SWIR wavelengths (LEDs, lasers, broadband illumination with monochromator)
    - Rear-side illumination capability relevant to FPA technologies
- Optical filters design, fabrication and characterisation

The NRC's patent and process IP portfolio for photodetector technologies demonstrates NRC's ability to innovate and enable the state-of-the-art in SWIR capabilities. The CPFC has also been fabricating single photon avalanche photodiode technologies in parallel to *p-i-n* detector technologies commercially for several years.

For those interested in developing advanced optoelectronic technologies, the CPFC pureplay model allows clients to retain their design IP while leveraging a process-related IP toolbox capable of supporting high-reliability, high-yielding process blocks needed for leading-edge design – including buried heterostructures (BHET) lasers and multi-growth DFB lasers, electro-absorption modulated lasers (EML), semiconductor optical amplifiers (SOA) and gain chips, and the interconnects and waveguides to build photonic integrated circuits. The CPFC has a team of commercially facing experts that work closely with customers throughout the device

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fabrication process to develop customized solutions that meet their specific needs and requirements.

## Opportunity details

License available

Patents pending:

- A. W. Walker, "Semiconductor devices with graded interface regions," US 2023/0395735 A1, Dec. 7, 2023
- A. W. Walker, P. Waldron, "Short range infrared imaging systems," US 2023/0099143 A1, Mar. 30, 2023

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