Doctoral Thesis in Information and Communication Technology

Process development of III-V-based infrared detectors

DAVID RAMOS SANTESMASES

Stockholm, Sweden 2024
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Doctoral Thesis in Information and Communication Technology
KTH Royal Institute of Technology
Stockholm, Sweden 2024
Als meus pares, José Manuel i Gemma,
al meu germà Pol, i a la meva estimada Laura
Sammanfattning

Typ-II Supergitter (T2SL) detektorer har revolutionerat fältet för infraröd (IR) avbildning och etablerat sig som spetsteknologi inom försvar, rymd och industriella tillämpningar. Dessa detektorer möjliggör större format och högre arbetstemperaturer (HOT) som minskar behovet av plats- och energikrävande kryogen kylning, vilket banar väg för IR-kameror med minskad Storlek, Vikt och Energiåtgång (SWaP).

Deras mångsidighet över olika IR-våglängdsband—långvåg, mellanvåg och kortvåg—kombinerat med den inneboende skalbarheten som är karakteristisk för III-V material, positionerar T2SL- teknologin som det ideala valet för nästa generations HOT och högupplösta (HD) detektorer.

Denna avhandling fokuserar på att förbättra tillverkningsprocessen för T2SL-detektormatriser för att minska ytströmmar som uppstår vid pixeletsning. Denna utmaning växer med minskad pixelstorlek och påverkar direkt en detektors maximala arbetstemperatur.

Genom att betrakta T2SL-detektorernas prestanda ges omfattande insikter i detektorernas elektriska egenskaper. Detta inkluderar analys av 1/f-brus och en detaljerad experimentell och kvantitativ modellering av ytströmmar, samt förslag på strategier för att reducera dessa. Vidare går studien in på fenomenet av optisk koncentration som uppstår i fokalplansmatriser (FPAn) och resulterar i ett ökat signal-brusförhållande. Slutligen analyseras graden av optiska och elektriska läckage mellan närliggande pixlar genom mätning och simulering av moduleringsöverföringsfunktionen.

Denna avhandling presenterar betydande framsteg i tillverkningsprocessen hos flera olika T2SL-detektorstrukturer vilket resulterat i anmärkningsvärda steg framåt för IR-detektorteknologin. Dessa inkluderar industriell produktion av FPAn med 640 × 512 pixlar med 15 μm:s pixelstorlek och med en arbetstemperatur på 150 K; produktionen av detektormatriser med 10, 7,5, och 5 μm pixel-till-pixelavstånd, alla kapabla att fungera vid 150 K; och demonstration av HD FPAn, med förmåga att fungera vid 150 K.

Nyckelord: infraröda detektorer, Typ-II supergitter, ytströmmar, hög arbetstemperatur, passivering, optisk koncentration, moduleringsöverföringsfunktion, brus.
Abstract

Type-II Superlattice (T2SL) detectors have revolutionized the field of infrared imaging, establishing themselves as the forefront technology in defense, space, and industrial applications. These detectors enable larger formats and higher operating temperatures (HOT) that minimize the need for bulky and energy-consuming cryogenic cooling, paving the way for imaging systems with reduced Size, Weight, and Power (SWaP).

Their versatility across various IR wavebands—long-wavelength, mid-wavelength, and extended short-wavelength—combined with the intrinsic scalability characteristic of III-V detectors, positions T2SL technology as the ideal choice for next-generation HOT and high-resolution (HD) detectors.

This thesis focuses on improving the manufacturing process for T2SL arrays to reduce surface leakage currents induced during pixel etching. This challenge becomes more pronounced with smaller pixels and directly affects the maximum operating temperature.

The investigation into T2SL detector performance provides comprehensive insights into the detectors' electrical characteristics. This includes $1/f$ noise analysis and a detailed experimental and quantitative modeling of surface leakage currents, proposing strategies for their reduction. Furthermore, the study delves into light-matter interactions within focal plane arrays (FPAs) to describe optical concentration effects to increase the sensitivity and provides Modulation transfer function measurements and simulations to discuss the resolution of T2SL arrays.

Employing diverse Sb-based T2SL detector photodiode structures, this thesis reports significant progress in the fabrication process, leading to remarkable achievements. These include the demonstration and industrial production of a $640 \times 512 - 15 \, \mu m$ format FPA operating at 150 K; the production of 10, 7.5, and 5 $\mu m$ pitch arrays, all capable of functioning at 150 K; and the demonstration of small-pitch HD FPAs, with the capability of operating at 150K.

**Keywords:** infrared detectors, Type-II superlattice, surface leakage, high operating temperature, passivation, optical concentration, modulation transfer function, noise.
Acknowledgements

As I reach the end of this journey, I would like to start from the beginning – the opportunity of doing this thesis. I want to thank IRnova and KTH for creating this position. It has been more than four years in which I have learned a lot, grown personally and professionally, and got to experience the feeling of doing something valuable. For all this, I have many people to thank.

My supervisors. Linda, your constant support and enthusiasm have made this work very easy. However, the most important thing is that you encouraged me to believe in myself and in the value of my contributions. That is the greatest gift a supervisor can give you and I cannot thank you enough for that. Per-Erik, I greatly appreciate your honesty and pragmatism during these four years. It has been a joy and privilege to work with you.

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Vull agrair de tot cor el suport dels meus pares Gemma i José Manuel i del meu germà Pol. El vostre suport constant i els valors que m'heu transmès són el que m'ha portat fins aquí. Por último, Laura, gracias por todo el apoyo en los días duros. Además, gracias a ti sé que esto no es tan importante.
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Author’s contribution: Automatizing the noise measurement set-up, electrical characterization, analysis of the characterization results and writing the manuscript.


Author’s contribution: passivation development, single pixel fabrication, electrical characterization, analysis of the characterization and simulation results and writing the manuscript.


Author’s contribution: two-step etch development, single pixel and array fabrication, electrical characterization of the single pixels, analysis of the characterization results, and writing the manuscript.


Author’s contribution: passivation development, single pixel fabrication and electrical characterization of the single pixels.

Author’s contribution: dry etching and passivation development, developing the simulation software, electrical characterization, analysis of the characterization and simulation results, and writing the manuscript.


Author’s contribution: MTF evaluation development, fabrication of the FPAs for MTF evaluation, MTF simulation, analysis of the characterization and simulation results, and writing the manuscript.

This work has also been presented in the following conferences:

1. Nordic Nanolab User Meeting 2022: Göteborg, Sweden
   *HOT SWaP and HD IR detectors based on Type-II superlattices* – Poster presentation

2. QSIP 2022: Kraków, Poland: *Impact of pixel size on the performance of HOT HD T2SL arrays* – Conference presentation

3. Freiburg Infrared Colloquium 2023: Freiburg, Germany: *Optical concentration in fully delineated MWIR T2SL detectors* – Poster presentation.

4. CSW 2023, Jeju, Korea: *Optical concentration in fully delineated MWIR T2SL detectors* – Conference presentation

5. Optics & Photonics Sweden 2023, Stockholm, Sweden: *Optical concentration in fully delineated MWIR T2SL detectors* – Poster presentation – Best poster award from IEEE Photonics Society
### Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>KTH</td>
<td>Royal Institute of Technology</td>
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<tr>
<td>BTB</td>
<td>Band to band tunnelling</td>
</tr>
<tr>
<td>T2SL</td>
<td>Type-II superlattice</td>
</tr>
<tr>
<td>TAT</td>
<td>Trap assisted tunnelling</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>PSD</td>
<td>Power spectral density</td>
</tr>
<tr>
<td>LW</td>
<td>Long-wavelength</td>
</tr>
<tr>
<td>MRTD</td>
<td>Minimum resolvable temperature difference</td>
</tr>
<tr>
<td>MW</td>
<td>Mid-wavelength</td>
</tr>
<tr>
<td>NETD</td>
<td>Noise equivalent temperature difference</td>
</tr>
<tr>
<td>eSW</td>
<td>Extended short-wavelength</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to noise ratio</td>
</tr>
<tr>
<td>HOT</td>
<td>High operating temperature</td>
</tr>
<tr>
<td>MTF</td>
<td>Modulation transfer function</td>
</tr>
<tr>
<td>SWaP(-C)</td>
<td>Size wight and power (cost)</td>
</tr>
<tr>
<td>MBE</td>
<td>Molecular beam epitaxy</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>Research and development</td>
</tr>
<tr>
<td>US</td>
<td>United states</td>
</tr>
<tr>
<td>GND</td>
<td>Ground</td>
</tr>
<tr>
<td>MCT</td>
<td>Mercury cadmium telluride</td>
</tr>
<tr>
<td>RIE</td>
<td>Reactive ion etching</td>
</tr>
<tr>
<td>InSb</td>
<td>Indium antimonide</td>
</tr>
<tr>
<td>ICP-RIE</td>
<td>Inductively coupled reactive ion etching</td>
</tr>
<tr>
<td>FPA</td>
<td>Focal plane array</td>
</tr>
<tr>
<td>IBE</td>
<td>Ion beam etching</td>
</tr>
<tr>
<td>PECVD</td>
<td>Plasma enhanced chemical vapor deposition</td>
</tr>
<tr>
<td>HD</td>
<td>High definition</td>
</tr>
<tr>
<td>ALD</td>
<td>Atomic layer deposition</td>
</tr>
<tr>
<td>BB</td>
<td>Black body</td>
</tr>
<tr>
<td>ALD</td>
<td>Atomic layer deposition</td>
</tr>
<tr>
<td>2D</td>
<td>Two dimensional</td>
</tr>
<tr>
<td>RBS</td>
<td>Rutherford backscattering spectroscopy</td>
</tr>
<tr>
<td>GaSb</td>
<td>Gallium antimonide</td>
</tr>
<tr>
<td>SIMS</td>
<td>Secondary ion mass spectroscopy</td>
</tr>
<tr>
<td>PDA</td>
<td>Photodiode array</td>
</tr>
<tr>
<td>OES</td>
<td>Optical endpoint spectroscopy</td>
</tr>
<tr>
<td>IDDCA</td>
<td>Integrated detector dewar cooler assembly</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscopy</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>FIB</td>
<td>Focused ion beam</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>-------------</td>
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<tr>
<td>CO</td>
<td>Carbon monoxide</td>
</tr>
<tr>
<td>SF$_6$</td>
<td>Sulphur hexafluoride</td>
</tr>
<tr>
<td>VOC</td>
<td>Volatile organic compound</td>
</tr>
<tr>
<td>MOCVD</td>
<td>Metal organic chemical vapor deposition</td>
</tr>
<tr>
<td>SRH</td>
<td>Shockley Read Hall</td>
</tr>
<tr>
<td>QE</td>
<td>Quantum efficiency</td>
</tr>
<tr>
<td>GR</td>
<td>Generation-recombination</td>
</tr>
<tr>
<td>TEM</td>
<td>Transmission electron spectroscopy</td>
</tr>
<tr>
<td>EDS</td>
<td>Energy-dispersive X-ray spectroscopy</td>
</tr>
<tr>
<td>ToF-ERDA</td>
<td>Time of flight-elastic recoiled detection analysis</td>
</tr>
<tr>
<td>NUC</td>
<td>Non-uniformity correction</td>
</tr>
<tr>
<td>DFA</td>
<td>Design for assembly</td>
</tr>
<tr>
<td>DFM</td>
<td>Design for manufacturing</td>
</tr>
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</table>
1. Introduction

The present manuscript is a compendium thesis that builds upon the peer-reviewed articles published by David Ramos Santesmases between 2020 and 2024 while working as an industrial PhD student at IRnova and with joint supervision from IRnova and the Royal Institute of Technology (KTH). The following text is written with the objectives to contextualize and complement the work described in the articles without compromising the intellectual property of IRnova around the production of its infrared (IR) detectors.

This introductory chapter lays out the motivations behind the development of Type-II Superlattice (T2SL) IR detectors, followed by the objectives of the research, the main contributions of the work, and concludes with an overview of the subsequent chapters.

1.1. Motivation – type II superlattice infrared detectors

IR detectors operating in the long-wavelength (LW), mid-wavelength (MW) and extended-short-wavelength (eSW) IR wavebands are essential for defence, space, and industrial applications. The high transmission of eSWIR, MWIR and LWIR through the atmosphere and low diffusion of light in these wavebands, makes the detection at long distances possible, even with fog, smoke, or dust. Therefore, eSWIR, MWIR and LWIR detectors meet the needs for night vision, surveillance, gas detection, global monitoring of land surface temperatures, and target identification applications.

III-V-based T2SL structures tailored for eSWIR, MWIR and LWIR detection can offer detectors with higher operating temperatures (HOT) and larger formats than traditional IR technologies without compromising their performance. These HOT T2SL detectors reduce the need for bulky and energy-intensive cryogenic cooling, resulting in low Size, Weight, and Power (SWaP) imaging systems. Furthermore, high-quality T2SL material can be uniformly grown over large wafers (up to 6”) using industrial Molecular Beam Epitaxy (MBE) equipment. This production scale significantly enhances fabrication yield and consequently lowers the cost of SWaP applications (low SWaP-C).

HOT-T2SL detectors enable low SWaP-C packaging of state-of-the-art infrared vision systems. In the United States (US), T2SL is already starting to replace the traditional Mercury Cadmium Telluride (MCT, HgCdTe) and Indium
Antimonide (InSb) technologies. This adoption has resulted in remarkable savings due to the more reliable and cost-efficient production of T2SL detectors compared with MCT [1].

In the US, the breakthrough of the T2SL technology came with the VISTA program (2011-2015), funded by the US Department of Defense. This program established the infrastructure for T2SL manufacturing, combining designs from the Jet Propulsion Lab [2], developing large-size substrates, transferring T2SL growth expertise to two primary growth foundries, and transferring the T2SL technology to major US infrared detector industries. This effort solidified the US technological leadership in T2SL, and translated into an intense activity in Asia, particularly in India, South Korea, Japan, and Israel —home to SCD [3], a global leader in IR Focal Plane Array (FPA) manufacturing. The transition to T2SL technology in Europe is, however, lagging significantly, with only a handful of actors involved in T2SL detector development, and with IRnova in the leading position for manufacturing of complete Integrated Detector Dewar Cooler Assembly (IDDCA) based on T2SL IR FPAs.

In this context, prior to the start of this thesis, IRnova started its production of T2SL detectors in 2014, focusing on 320 × 256 format detectors with 30 µm pitch for gas sensing. In 2019 IRnova started full scale production of 640 × 512, 15 µm pitch detectors and in 2020, IRnova released a 640 × 512 – 15 µm pitch full mid-waveband detector with a mini-cryocooler, making it the first European-manufactured SWaP T2SL detector. The detector achieved a notable maximum operating temperature of 110 K; however, the manufacturing process hindered the performance of the small photodiodes (≤ 10 µm) required for high-resolution (HD) arrays (≥ 1280 × 1024) and prevented their 15 µm pitch format detectors from operating at higher temperatures. This degradation was caused by surface leakage current, a parasitic current arising from the pixel’s sidewall defects with increasing contribution as the pixels become smaller. Consequently, reducing surface leakage current is of great importance to meet the increasing demand for small-pitch high definition (HD) detectors.

The aim of this thesis was to improve the manufacturing process of T2SL arrays to further increase the operating temperature and resolution off IRnova’s T2SL detectors. Therefore, the work performed first focuses on the investigations of surface leakage currents and ends by studying the impact of the array geometry on the performance of T2SL HD detectors.
1.2. Research objective

The main goal of this thesis was to increase the operating temperature of Sb-based T2SL infrared detectors with a fabrication process compatible with high-resolution detectors. This research can be broken down in four objectives:

- Objective 1: Develop a fabrication process with reduced surface leakage current.
- Objective 2: Transfer the optimized process in the fabrication of \(640 \times 512 - 15 \mu m\) pitch detector format to produce full MWIR HOT - FPAs.
- Objective 3: Design and fabricate small pitch detector arrays (\(\leq 10 \mu m\) pitch) compatible with HOT performance.
- Objective 4: Integrate the HOT small pitch arrays with a matching ROIC to demonstrate a HOT-HD T2SL-based FPA.

To achieve these objectives three Sb-based T2SL detector photodiode structures were used: p-type absorber with p-on-n polarity, p-type absorber with n-on-p polarity and n-type absorber with p-on-n polarity. Table 1 shows the progress achieved for each case during the thesis period and compares the detectors’ performances with different absorber doping (p-type, n-type) and detector polarity (p-on-n, n-on-p, p-on-n) across the four objectives. Symbols indicate progress: '✔' for achieved, '×' for failed, and '-' for not applicable.

<table>
<thead>
<tr>
<th>Detector polarity</th>
<th>p-type</th>
<th>n-type</th>
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<tbody>
<tr>
<td>p-on-n</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>n-on-p</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>p-on-n</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Objective 1</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Objective 2</td>
<td>✔×</td>
<td>-</td>
</tr>
<tr>
<td>Objective 3</td>
<td>×</td>
<td>-</td>
</tr>
<tr>
<td>Objective 4</td>
<td>-</td>
<td>×</td>
</tr>
</tbody>
</table>

Table 1: Progress of the different Sb-based T2SL detector structures in achieving the thesis objectives.

1.3. Research contribution

The following contributions were made to fulfill the research objectives:

- Contribution 1: 1/f noise analysis in T2SL detectors.
- Contribution 2: Experimental description and quantitative modeling of the surface leakage.
- Contribution 3: Demonstration of a \(640 \times 512 - 15 \mu m\) format FPA operating at 150 K.
• Contribution 4: Description of the light matter interactions in the FPAs.
• Contribution 5: Demonstration of 10, 7.5 and 5 µm pitch arrays with capability of operating at 150 K.
• Contribution 6: MTF measurements and simulations on T2SL detector arrays.
• Contribution 7: Demonstration of a 1280 × 720 – 7.5 µm format FPA with capability of operating at 150 K.

1.4. Thesis organization

This thesis is organized in 8 chapters as follows:

• Chapter 1: Introduces and provides the structure of the thesis.
• Chapter 2: Outlines the figures of merits of IR detector arrays.
• Chapter 3: Presents the fabrication methods and characterization techniques used in this work.
• Chapter 4: Complements the results on p-type p-on-n Sb-based T2SL detectors.
• Chapter 5: Complements the results on p-type n-on-p Sb-based T2SL detectors.
• Chapter 6: Complements the results on n-type p-on-n Sb-based T2SL detectors.
• Chapter 7: Complements the results on quantum efficiency and resolution.
• Chapter 8: Concludes the thesis and provides possible future research paths.
2. Infrared detectors

IR detectors can be categorized into thermal and photonic families. Bolometers, thermopiles, and pyroelectric detectors fall under thermal detectors, and photoconductors and photovoltaic detectors are classified as photonic detectors. Detectors also come in diverse formats, ranging from single elements to linear and 2-dimensional (2D) arrays. In this thesis, the focus is on the development and fabrication of 2D arrays of cooled photon detectors utilizing T2SL photodiodes as the detection device.

A superlattice is a periodic arrangement of alternating thin (few nm) semiconductor layers, combined to create a thick absorber (few µm). This material is used in a photodiode structure which absorbs the incoming photons and generates an electric signal. Fabricating 2D arrays of these photodiodes (= pixels) and connecting them to a read out integrated circuit (ROIC), the electric signal from each pixel in the array can thus be measured and used to form an image.

Figure 1 illustrates the different components and manufacturing steps needed to assemble these imaging detectors. The process starts with designing the T2SL photodiode structure using quantum mechanical, electrical, and optical simulation tools. The detector structure is subsequently grown on a wafer substrate, typically Gallium Antimonide (GaSb). Photodiode arrays (PDAs) are then fabricated from the grown material, with the targeted detector's format and pitch size (pixel to pixel distance). Next, the PDA is hybridized to the ROIC with indium interconnects forming the Focal Plane Array (FPA). This hybrid structure is mounted on ceramics and integrated into a cooling system. The resulting system, the Integrated Dewar Detector Cooler Assembly (IDDCA), is then ready for further integration into an IR camera with the corresponding optics.

IRnova covers the entire value chain in detector manufacturing – from the T2SL structure design to the cooler assembly. However, this thesis focuses on developing the PDAs' fabrication process to improve the IDDCA performance.
This chapter offers an overview of the system and outlines the link between the PDA and IDDCA performance. First, the chapter describes the origin of infrared radiation and the significance of the IR scene in the performance of the detectors. Secondly, it delves into the specifics of T2SL structures as material for IR detection. Thirdly, it outlines the key performance metrics employed for the characterization of FPAs and finalizes by describing IDDCA and the role of the cooler in setting the system's size, weight, power, and cost.

### 2.1. The infrared scene

An IR scene is interesting for two main reasons: the information about the temperature, and the atmospheric transmission. For common terrestrial temperatures (300 K) most of the radiation is emitted in the infrared spectra with a peak emission wavelength around 10 \( \mu m \) (Figure 2). Therefore, the IR spectrum can be used for imaging in the absence of an external light source. The relation between the emittance and the temperature of the object is given by Plank’s law, Equation 1 [4]:

\[
M(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{\exp\left(\frac{hc}{\lambda k_B T}\right) - 1}
\]

- \( M(\lambda, T) \) spectral emittance
- \( h \) the Plank constant
- \( c \) the light speed
- \( \lambda \) the wavelength
- \( k_B \) the Boltzmann constant
- \( T \) the temperature of the object
The Plank’s law defines the intensity of the emitted signal, however for the detector system other aspects of the radiation such as thermal contrast defined by \( C = \frac{\partial M(\lambda, T)}{\partial T} \frac{1}{M(\lambda, T)} \) or even the diffraction limit must be considered.

Figure 2 shows the emittance of a blackbody at 200, 300 and 400 K together with the thermal contrast at 300 K as a function of the wavelength. For the emittance, the maximum flux is located around 10 and 5 \( \mu \)m for a blackbody at 300 and 400 K, respectively. On the other hand, the thermal contrast with respect to a 300 K background increases with decreasing wavelength doubling from 1.5 \%/K at 10 \( \mu \)m to 3\%/K at 5 \( \mu \)m. The choice of the spectral band will therefore depend on both the emittance of the object to detect, and the contrast information contained in the radiation.

![Figure 2. Emittance of a blackbody at 200, 300 and 400 K, the thermal contrast for a 300K background as a function of the wavelength.](image)

Secondly, the infrared spectrum’s significance lies in its atmospheric transmission, particularly for long-range imaging. Figure 3 shows the atmospheric transmission calculated with the ATRAN model [5]. Three IR spectral bands present high atmospheric transmission:

- Extended short-wavelength infrared (eSWIR): 1 - 2.5 \( \mu \)m
- Mid-wavelength infrared (MWIR): 3 - 5.5 \( \mu \)m
- Long-wavelength infrared (LWIR): 8 - 14 \( \mu \)m.

Specific application requirements, including desired resolution, object temperature, and required sensitivity, will determine the selection of the spectral range for detection.
Figure 3. Simulated atmospheric transmission calculated by the ATRAN model at an altitude of 5640 m longitude 30° and Zenith angle of 0° [5].

The IR transmission depends on the chemical composition of the scene under observation. Therefore, besides long-range imaging the IR detectors can be used for gas detection. Optical gas imaging is a technique to detect gases with absorption in specific wavelength ranges. For example, it can target carbon dioxide (CO$_2$) and carbon monoxide (CO) at 4.3 µm and 4.6 µm, respectively. Gases like sulphur hexafluoride (SF$_6$), ammonia, and ethylene are detectable at 10.55 µm, and volatile organic compounds (VOC) such as methane, ethane, and propane have absorption spectra around 3.3 µm. The detection of hazardous gas leaks is for instance used in monitoring of industrial plants.

The object’s temperature and atmospheric transmission determine the radiation levels in an IR scene. However, it is the system’s optics that defines the portion of the scene captured in the IR image. Therefore, the optics, through their transmission and optical aperture, ultimately control the flux of incoming photons to the detector array located at the focal plane of the imaging system. The camera equation (G#) from Equation 2 describes the proportion of scene irradiance reaching the focal plane [6]:

$$G# = \frac{T_{opt} M(\lambda, T)}{1 + 4F^2}$$

(2)

where $F$ is the f-number, a measure of the light-gathering ability of an optical system defined by the ratio of the focal length and the optical aperture, and $T_{opt}$ is transmission of the optical system. Consequently, the detector’s output signal
is influenced not only by the scene and the detector's sensitivity but also by the optical system's characteristics.

Optics with a low f-number channel more radiation to the detector, reducing the dependence on detector sensitivity. However, these optics increase the camera system's volume and weight and limit the maximum distance for identification of objects due to saturation of the detector. On the other hand, high f-number optics, although delivering fewer photons to the detector, enable the identification of distant objects and lead to more compact camera designs [6,7].

The focus of this thesis is on enhancing the detector sensitivity at high temperatures for high-performance applications. This improvement aims to leverage the SWaP benefits enabled by T2SL technology without the need for bulky optics.

2.2. T2SL photodiodes for IR detection

T2SL-based IR detectors are composed of a superlattice material used as the absorbing layer in a photodiode device. The superlattice has its energy band gap engineered for the absorption of IR photons, while the photodiode, under reverse bias, facilitates the transfer of photo-generated carriers to the ROIC. However, in a photodiode, the current in reverse bias comprises the carriers generated from external radiation (photocurrent) and those from internal thermal excitation (dark current). The balance of these current components and their random fluctuation over time (electronic noise) determine the photodiode's sensitivity to IR radiation.

This section discusses the characteristics of the T2SL structure as an absorbing material, its integration in a photodiode structure, and examines the mechanisms behind photocurrent, dark current, and noise in T2SL photodiodes.

Absorbing material

Figure 4 shows a diagram of different semiconductors' bandgap and their respective lattice constants at 77 K highlighting the spectral ranges corresponding to the eSWIR, MWIR, and LWIR.

Figure 4 shows that the bandgap is strongly linked to the lattice constant for most materials. This dependence constrains the bandgap tunability of each component by the lattice constant of the substrate used for its growth.
This is not the case for HgCdTe (MCT), where the bandgap ranges from LWIR to eSWIR, with a nearly constant lattice parameter. That is the reason why MCT is the material classically used for IR detection.

![Energy and gap versus lattice constants of semiconductors and the eSWIR, MWIR and LWIR spectral ranges at 77 K][8,9].

However, there are two main incentives to develop III-V semiconductor technology as an alternative to MCT. The first is the stronger and less ionic chemical bonding in III-V semiconductors, resulting in more stable and uniform FPAs [1,10]. The second is the larger substrates available for the growth of III/V materials, compared to the small CdZnTe substrates used for MCT (typically smaller than 3" square), limiting the production's manufacturability and scalability.

In the short wave, InGaAs detectors have demonstrated high sensitivity, uniformity, and scalability at room temperature, thanks to the availability of large InP substrates (typically 4""). However, the lattice-matched growth to InP limits the cut-off wavelength to 1.7 µm and extending the cut-off wavelength (to ~2.5 µm) induces mismatch defects, which lower the sensitivity and uniformity of the detectors.

In the mid-wave, InAs$_{0.91}$Sb$_{0.09}$ grown lattice matched to GaSb (also referred to as XBi) is used for its uniformity, sensitivity, and scalability thanks to the large GaSb wafers (up to 6""). However, it does not cover the full mid-wave range as the cut-off wavelength is limited to a 4.1 µm. On the other end, pure InSb detectors allow covering the full MWIR band, but with an operating temperature inherently limited to 80 K.
In this context, the development of III-V based quantum structures, such as quantum well-infrared photodetectors (QWIPs) and T2SLs, circumvents the lattice constant-bandgap limitation.

GaAs/AlGaAs QWIPs grown on GaAs can be designed with a peak absorption to detect MWIR and LWIR radiation. Nowadays QWIP is a well-established technology in the LWIR regime and stands out for its stability, high pixel-to-pixel uniformity, and high-pixel operability [11]. However, the scarcity of MWIR photons coupled with the narrow absorption peak limits their implementation in the MWIR.

This thesis focuses on broadband absorption in the MWIR regime and for that T2SL structures is an excellent choice. Superlattices for infrared detection can offer bandgap tunability similar to the MCT compound (from eSWIR to LWIR [12]) using materials with a lattice constant around 6.1 Å, namely InAs, GaSb and AlSb. Combining these materials enables the growth of thick detector structures lattice-matched (or strain-balanced) to the GaSb substrate [13].

A superlattice consists of a periodic arrangement of alternating thin layers of different semiconductors. The working principle of T2SLs is based on a two-component multilayer material in which, due to the bandgap offset of the components, the wavefunctions of the lowest conduction sub-band and highest valence sub-band are localized in two different semiconductors. The typical superlattices used as absorbing material of IR detectors are the InAs/InAsSb and InAs/GaSb SLs [12,14].

To illustrate their working principle, Figure 5a shows a schematic of the InAs/GaSb superlattice and Figure 5b the cut-off wavelength of the InAs/GaSb superlattices as a function of the InAs layer thickness with a fixed GaSb thickness of 8 and 12 monolayers (ML). Figure 5a illustrates the broken-gap band alignment of InAs and GaSb, with the electrons and holes spatially separated and localized in either layer. The spread into neighboring layers of wavefunctions enabled by tunneling effect through the thin barrier forms the minibands across the structure. With the transport of the electrons and holes in the minibands, the superlattice resembles a bulk material with a resulting bandgap, which is the energy difference between the top of the first heavy hole minibands and the bottom of the first conduction minibands, that can be smaller than the materials composing the SL.

Figure 5b demonstrates that the superlattice bandgap can be tailored by adjusting the thickness of the individual layers constituting the superlattice, due to the spatial delocalization of the sub-bands. This highlights one of the advantages of the T2SL material structure, i.e. the capability of tuning the cut-
off wavelength of the detector from eSWIR to LWIR, simply by adjusting the thicknesses of the SL layers. Material flexibility using semiconductor from the 6.1 Å group also allows for lattice-matched heterostructures using various superlattices for improved detector performance (see section Device structure) or even the growth of dual-band detectors with different absorber bandgaps in the same material stack.

Figure 5. Schematic band diagram showing the broken gap alignment between InAs and GaSb and the SL energy band gap between the heavy hole and electron minibands (a) and example of the bandgap tunability of InAs/GaSb SL as a function of the thickness of the individual layers composing the superlattice period (b).

The same working principle applies to the InAs/InAsSb T2SL structures. However, the small bandgaps of constituent materials and the required larger superlattice period thickness for these structures result in limited optical tunability to mid- and long-wavelength infrared (MWIR and LWIR) and reduced absorption coefficients at longer cut-off wavelengths [14].

MBE is typically the chosen method for the growth of T2SL IR detector material for its uniform layer, interface management, thickness control and low defect density of Sb-based layers. This technique makes III–V-based IR FPAs stand out regarding operability, uniformity, stability, scalability, producibility, and affordability. Furthermore, ongoing investigations in using Metalorganic Chemical Vapor Deposition (MOCVD) for T2SL growth and recently demonstrated MOCVD-grown FPA promise further cost reductions [15-18].

Device structure

There are two different types of device architectures to collect the minority carrier generated in the T2SL absorber region:
• **pn photodiode:** In traditional pn photodiodes, band bending within the depletion region of a pn homojunction blocks majority carriers, allowing the extraction of photo-generated minority carriers. However, this structure faces significant dark current due to high Shockley-Read-Hall (SRH) generation in the depletion region.

• **Barrier detector design:** barrier detectors use a heterojunction with a larger band gap material (a barrier layer) inserted between the absorber and the collector contact that substitutes the pn homojunction [19]. This band offset of the barrier layers is chosen to block the majority carriers while allowing the unimpeded transport of the photo-generated minority carriers. In this design, the barrier layer contains the electric field, suppressing the SRH current from the absorber region therefore reducing the dark current below standard pn photodiodes.

Moreover, these structures allow for increasing the photo-generated carrier collection by terminating absorbers' end opposite to the collector with a heterojunction with a larger bandgap material impeding the transport of minority carriers and, therefore, deflecting them towards the collector (like the back surface field in solar cells) [13].

Building barriers requires careful material selection for lattice matching and proper band offsets. For that, one can use ternary or quaternary alloys or further exploit the flexibility of the superlattice design. Examples include electron-blocking barriers made from GaSb/AlSb and InAs/GaSb superlattices and hole-blocking barriers from complex supercells like the "W" or "M" structures [13].

All detector structures studied in this thesis use a double heterostructure configuration for improved performance. Figure 6 shows a schematic of the double heterostructure for the p-on-n with a p-type absorber (a), the n-on-p with a p-type absorber (b), and the p-on-n with n-type absorber (c). The figure illustrates the blocking of the majority carriers and the deflection of the minority carriers towards the collector for each case. Finally, the figure indicates the backside radiation and position of the top and bottom contacts to illustrate the structure's orientation for the actual pixel device with the pn junction on the bottom of the pixels for case-a and on the top for cases b and c.
Figure 6. Schematic illustration of the double heterostructure for the p-on-n with a p-type absorber (a), the n-on-p with a p-type absorber (b), and the p-on-n with n-type absorber (c) studied in this thesis.

Photocurrent

The photocurrent of the detector is determined by the number of photons that reach the detector and the fraction of collected photocarriers per incoming photon (quantum efficiency (QE)). The expression for the photocurrent is given in Equation 3 [20].

\[
I_p = \int_{\lambda_o}^{\lambda_1} \left[ \varepsilon M(\lambda, T) \frac{T_{opt} T_{atm} \lambda}{1 + 4F^2 \frac{\lambda}{hc}} \right] A_o q QE(\lambda) \, d\lambda
\]  

The photon flux density impinging into the detector material is expressed in the first part of the integral with \( \varepsilon \) being the emissivity of the object, \( T_{atm} \) being the transmission of the atmosphere and the parameters corresponding to the camera equation, \( T_{opt} \) and \( F \). In the second part of the integral \( A_o \) corresponds to the area of the detector contributing to the photocurrent and the QE which results
from the total absorption and the collection efficiency. From all these factors only, the QE is linked to the T2SL structure.

The QE, however, is not an intrinsic material parameter, as it will depend, for instance, on the thickness of absorbing material and its relation to the transport mechanism of the photo-carriers. Moreover, phenomena such as optical coupling via plasmonic resonance, antireflective coating, or reflective metals make the QE dependent on the structure's design and its fabrication process. However, because of its direct impact on the photocurrent density, it is the parameter used typically for review and comparison of different detector technologies.

Figure 7 presents the reported QE performance for various detector material technologies as a function of the cut-off wavelength, from Ref [21].

Figure 7 shows that T2SL structures are at the state of the art of IR detector technology regarding its optical performance in the MW with reported values up to 80%, however the maximum reported QE decreases for longer wavelengths falling below the MCT level in the LW range.

![Figure 7. QE as a function of the cut-off wavelength for different detector technologies from [21]](image)

The lower QE of T2SL in the LWIR is due to the dependance of the absorption coefficient on the superlattice period thickness. The absorption coefficient of a superlattice is given by Equation 4 [22]:

$$\text{Absorption coefficient} = \text{Equation 4}$$
\[ \alpha(\omega) = \frac{q^2 \chi_{cv}^2}{n_r c m_0^2 \omega \varepsilon_0 \Omega} |d_{cv}|^2 D_{cv}(\omega) \]

\[ |d_{cv}|^2 = |\langle u_i | p \varepsilon | u_j \rangle| I_{cv}^2 \]

Where \( n_r \) the refractive index of the material, \( \Omega \) the material volume, \( \chi_{cv}^2 \) the electric dipole matrix element of the optical transition, \( D_{cv} \) the joint density of states \( m_0 \) the free electron mass and \( |d_{cv}|^2 \) is the optical matrix element between the conduction band and valence band wavefunctions, with \( u_j \) corresponding to the block density of states and \( I_{cv}^2 \) the wavefunction overlap.

According to Equation 4 the absorption coefficient directly depends on the wavefunction overlap. As a result, for very thin superlattice periods the absorption coefficient will be high as the wells will be strongly coupled, while for thicker periods the absorption coefficient will be lower. The period thickness, however, is also used to tune the cut-off wavelength of the absorber. As a result, the absorption coefficient will depend on the spectral range.

To illustrate this effect, Figure 8 shows the measured absorption coefficient of an InAs/GaSb T2SL detector design for which the absorbers’ is tuned from 3.5 to 13.5 µm in cut-off wavelength by increasing the thickness of the superlattice period. Figure 8 demonstrates the tunability of T2SL structure however, it shows that the thicker wells required for the absorption of LWIR have a negative impact on the absorption coefficient.

Figure 8. Absorption coefficient as a function of the wavelength for different T2SL detector designs from IRnova, with cut-off wavelengths ranging from eSWIR to VLWIR.

The lower wavefunction overlap in the LWIR region is the reason for the reduced QE observed in T2SL material within this range in Figure 7. This constraint is a
challenge for LWIR detectors based on T2SL, leading to the development of QE enhancement methods, such as plasmonic resonances or metastructures. These techniques improve optical coupling during fabrication when the material alone cannot achieve the desired absorption.

The limitation on the other side of the IR spectra (around 2 μm cut-off wavelength) is anticipated to be set by the growth capabilities of thin superlattice layers. The interfacial layer roughness and potential local strain fluctuations can impact the mobility of the carriers degrading the transport properties in superlattices with thin periods. Nevertheless, its development is still promising and the potential InAs/GaSb superlattices for eSWIR detection is discussed in Article III.

**Dark current**

Dark current originates from charge carriers in the detector material that are not produced by photon absorption. These carriers are thermally generated, causing an increase in dark current with rising temperature. This temperature-dependent behavior sets the operating temperature limits for FPAs, as detector sensitivity degrades with a higher dark current to photocurrent ratio (see section 2.3). Consequently, high-sensitivity photon IR detectors typically operate between 50 to 200 K, necessitating advanced cooling systems.

Understanding and minimizing the impact of dark current is therefore crucial for optimizing imaging system performance. Dark current is usually expressed as dark current density, $J_d = I_d / A_e$ (A/cm²), making it independent of the electrical active area ($A_e$), i.e., the pixel area. The components of dark current in a photodiode are detailed below:

- **Diffusion current** results from the diffusion of thermally generated minority carriers in the quasi-neutral region to maintain charge neutrality. To contribute to the current the carriers must be within the diffusion length away from the depletion region. The expression for the diffusion current in a pn junction where $L_{diff} <$ absorber thickness is given by [23]:

$$
J_{diff} = J_0 \left[ \exp \left( \frac{qV}{k_BT} \right) - 1 \right]
$$

$$
J_0 = q n_i^2 \left( \frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A} \right)
$$

With $V$ being the bias on the detector, $n_i$ the intrinsic carrier concentration, with $D_{n,p}$ being the diffusion coefficient for electron and holes, $N_A$ and $N_D$, the
acceptor and donor concentration, and $L_{n,p}$ the diffusion length for electrons and holes given by $L_{n,p} = \sqrt{D_{n,p}\tau_{n,p}}$, where $\tau_{n,p}$ is the lifetime of the respective carriers. Under reverse bias, the activation energy of the diffusion current corresponds to the bandgap of the absorber region due to the dependence with $n_i^2$.

- **Generation-recombination (GR) current** originates from the SRH generation through traps states in the depletion region ($W$) [24].

$$J_{GR} = q \int_0^W R_{SRH} dz$$

$$R_{SRH} = \frac{pn - n_i^2}{\tau_p \left( n + n_i \exp\left(\frac{E_t}{k_B T}\right) \right) + \tau_n \left( p + n_i \exp\left(-\frac{E_t}{k_B T}\right) \right)}$$

(6)

Where $p$ and $n$ are the hole and electron carrier concentration and $E_t$ is the difference between the trap level and the intrinsic fermi level. Typically, GR dark current is reported with a half bandgap activation energy due to the dependence with $n_i$.

As discussed in the Device structure section, the GR current component can be suppressed at the operating bias by using photodiodes with a barrier structure. Barrier detectors are designed to confine the depletion region in a layer with a higher bandgap than the absorber and ideally with GR activation energy higher than the diffusion current from the absorber. Furthermore, the impact of the GR in the total current can be further reduced by confining $J_{GR}$ in an area smaller than the pixel (see section 4.5).

- **Tunneling current** arises from carriers that cross the pn junction by transitioning from the valence band to the conduction band. This can be a direct transition (band to band tunneling (BTB)) or assisted by trap states in the bandgap (trap-assisted tunneling (TAT)). Both types of tunneling have very little activation energy which results in low temperature dependence. These currents, however, can be dominant under high reverse bias when the tunneling probability increases with the band alignment [25]. The use of barrier structures is also beneficial for tunneling suppression.

- **Surface leakage current** is a dark current component related to the fabrication process. It originates from the defects created during the pixel delineation (i.e., mesa etch). These defects can alter the carrier concentration at the detector sidewall and result in additional parasitic dark current. The
mechanism of this current can be majority carrier drift, tunnelling, GR, and diffusion [26]. However, as it results from a parasitic conduction along the pixel sidewall, it will increase the dark current density of the pixel as the surface-to-volume ratio of the pixel increases.

The total dark current density in a photodiode can be decomposed into a bulk ($J_{bulk}$) and a surface ($J_{surface}$) component according to [26,27]:

$$J_d = J_{bulk} + \frac{P}{A} \cdot J_{surface}$$

(7)

where $P$ and $A$ correspond to the perimeter and area of the photodiode, respectively. This makes the small photodiodes ($\leq 10 \mu \text{m}$) required for high-density pixel arrays ($\geq 1280 \times 1024$) more prone to dark current degradation. Understanding and minimizing surface leakage current is crucial for the performance of high-resolution FPAs operating at high temperatures and is one of the main focus areas in this thesis (Articles II, III, and IV).

The total dark current density is the sum of all these components (diffusion, GR, tunneling and surface leakage) with the diffusion current being the lower limit of the current. This makes the dark current density depend strongly on the electrical material parameters such as $n_i$ and the minority carrier lifetime.

The dependence of the current on $n_i$ is the reason why eSWIR detectors operate closer to 200K while LWIR detectors operate below 100 K. Moreover, the dependence of the current in the carrier lifetime is what links the detection to the material quality as the carrier lifetime, is defined by the SRH, Auger and radiative processes in the material [28]:

$$\tau^{-1}_{total} = \tau^{-1}_{SRH} + \tau^{-1}_{Auger} + \tau^{-1}_{rad}$$

(8)

However, the dark current also depends on the design, the fabrication process, and the pixel size. Therefore, from device perspective, the review and comparison of different detector technologies uses directly the dark current density as the metric for comparison. The dark current density in IR detectors is typically compared to the Rule 07 level. Rule 07 is an empirical expression that defines the state-of-the-art performance of diffusion-limited MCT detectors as a function of the temperature and cut-off wavelength of the absorber [29].

Figure 9 compares the reported dark current densities for various detector material technologies to the Rule 07 level as for the eSWIR (a) from ref Article III and Ref. [30,31], and the MWIR (b) and LWIR (c) spectral ranges from Ref
The comparison is shown as a function of the inverse cut-off wavelength/operating temperature product due to the dependence of the dark current density on the thermal excitation across the bandgap.

Figure 9. Dark current as a function of the cut-off wavelength/operating temperature product for different detector technologies for the eSWIR (a), MWIR (b) and LWIR (c) spectral ranges. From Article III and Ref. [21,30,31]

Figure 9 shows that T2SL detectors reach state-of-the-art dark current density performance for the eSWIR, MWIR and LWIR detector technology. Figure 10 shows a detailed state-of-the-art comparison in the MWIR spectral range since it is the focus of this thesis. Figure 10 shows the dark current density level at 150 K for the most advanced III-V detector designs as a function of the wavelength and compares it to the level of the 10 µm pitch detector arrays fabricated at IRnova. The graph highlights the progress achieved during the development of this thesis. To the best of our knowledge, this dark current level is one of the best reported so far in the literature for T2SL-based detectors, moreover, it is reported...
for a pixel pitch compatible with HD arrays and for a detector covering full midwave IR.

![Figure 10](image.png)

**Figure 10.** Dark current at 150 K as a function of the cut-off wavelength for the main III-V midwave detector designs. Rule07 at 150 K as a function of the cut-off wavelength and comparison with the state-of-the-art [32-35].

By design, the dark current density can be further lowered. For example, by restricting the absorber volume to a thickness thinner than the diffusion length, the dark current will bypass the diffusion-limit. However, this strategy can impact the absorption and therefore the generated photocurrent. This strategy is used in plasmonic based detectors which boost the absorption by exiting plasmonic resonance at the top surface of the absorber and therefore decouple the photocurrent generation from the absorber thickness [36].

Ultimately, by fabrication, the total dark current can be reduced by lowering $A_e$. Classically, optical, and electrical areas are the same (i.e., the semiconductor area), and reducing the electrical area would not increase the photo-to-dark current ratio. However, photon-trapping structures or optical concentration lenses can be implemented by processing the material to decouple the photocurrent generation from the absorber volume [37-39]. **Article V** shows the result of optical concentration in T2SL detectors.

**Noise**

The noise in the detector is due to the random, spontaneous fluctuation of the current signal over time. Due to its random nature, the noise is defined in terms of power and characterized in the frequency domain. The power spectral density
(PSD) is given by the autocorrelation function [40] and describes how the noise power is distributed over frequency (A²/Hz). The current noise root mean square is given by:

\[ i_{n,rms} = \sqrt{\int_{f_1}^{f_2} S_i d\tilde{f}} \]  \hspace{1cm} (9)

Where the total PSD of the current noise is \( S_i \), and the bandwidth is defined by the integration time as \( \Delta f = f_2 - f_1 = (2\tau_{int})^{-1} \). Different noise mechanisms will have different characteristic PSDs and will define the total noise as \( S_i = \sum S_{i,n} \).

The possible noise mechanisms in a photodiode detector are listed below:

- **Thermal Noise** is generated by the thermal agitation of the charge carriers inside an electrical conductor. It only depends on the resistance of the device \( R \) and the temperature \( T \):

\[ S_{i,thermal} = \frac{4k_B T}{R} \]  \hspace{1cm} (10)

- **Shot noise** originates from the discreet nature of carriers. The random current flowing across a potential barrier, like a p-n junction, can therefore be modelled by a Poisson process [40].

\[ S_{i,shot} = 2qI \]  \hspace{1cm} (11)

- **GR noise** originates from traps capturing or releasing carriers and therefore causing variation in the current signal versus time. The PSD of the fluctuation in the number of carriers is given by [40]:

\[ S_{i,GR} = I^2 \frac{N_T}{N^2} \frac{\tau_T}{1 + (2\pi f \tau_T)^2} \]  \hspace{1cm} (12)

Where \( N_T \) is the number of traps, \( N \), the number of carriers and \( \tau_T \) the time constant for the transitions.

- **Random Telegraph Signal (RTS) noise or flickering** is a special case of GR noise which involves only a few traps. In this case the current switches between two or more states. The discrete switching events due to random trapping and trapping of carriers is displayed in the time domain as a flickering of the diode signal [40,41].
1/f noise is a type of electronic noise with a PSD inversely proportional to frequency. Its origin is still unclear [40,42]; however, it occurs in almost all electronic devices. It is described empirically in T2SL detectors by [43]:

\[ S_{i,1/f} = \sum_{f}^{1} \alpha_i I_i^{\beta_i} \]  \hspace{1cm} (13)

Where \( I_i \) is the i-component of the dark current, and \( \alpha_i \) and \( \beta_i \) are empirically determined coefficients. In Article I the noise coefficients for the dark current components of the p-type p-on-n structure are extracted and found to be among the lowest reported in the literature [44].

The lower limit on the noise of a photodiode detector is given by thermal and shot noise. These two noise components are independent of the frequency (white noise) and will scale proportionally with the integration time. However, since the resistance of the photodiodes is very high and the detectors operate at cryogenic temperature, the shot noise is typically the component that dominates the white noise in the arrays.

In contrast, parasitic components like GR, RTS and 1/f noise introduce additional noise to the device, particularly in the low-frequency range, where they can become dominant over white noise. This low-frequency noise can significantly impact device performance in applications requiring extended integration times, such as space-based applications [45]. Additionally, from the ergodic property of noise, by which the distribution for one ensemble element over time is equal to the distribution over the whole ensemble at a chosen point in time, non-uniformities in the array signal are attributed to the manifestation of the low-frequency noise [46] (see section 2.3). Nevertheless, at a pixel level, for the integration times required for live video, the photodiodes are typically assumed to be limited by shot noise of the total dark current, \( S_i = 2q(I_d + I_p) \). [47]

### 2.3. Figures of merit of the Focal Plane Array

The FPA is a 2-dimensional matrix of photodiode elements (pixels) situated at the focal plane of the imaging system connected by indium interconnects to a ROIC through a hybridization process. The ROIC is a silicon chip used to accumulate the signal from each pixel of the PDA and transfer the integrated signal into the subsequent electronic stages that will result in an IR image.

The storage capacity within each pixel depends on the size of the capacitor cell, which is constrained by the pixel size. Progress in the photodiode technology
must be matched by ROIC development since the hybrid of the two components is what generates the output signal of the scene.

The FPA's performance is therefore shaped by the collective detection capabilities of the array of photodiode elements and the associated ROIC, rather than solely by the electro-optical characteristics of individual photodiodes discussed in the previous section. The main performance indicator for the FPAs is the minimum resolvable temperature difference (MRTD), which combines both its sensitivity and resolution [48].

\[
MRTD = \frac{\text{NETD}}{\text{MTF}}
\]

The noise equivalent temperature difference (NETD) describes the sensitivity. It refers to the temperature difference that results in a signal-to-noise ratio (SNR) of one. As a result, a small NETD indicates good thermal sensitivity. For the resolution, the Modulation Transfer Function (MTF) is the metric that describes how a system reproduces contrast of the different spatial frequencies of the object; therefore, higher MTF signifies better detail recognition.

**Noise equivalent temperature difference**

The sensitivity of an array is determined by distribution of the pixel’s response under uniform illumination. The distribution of the pixel response is analyzed over time and spatially, which conforms to the temporal and spatial NETD, respectively.[49]

- **Temporal NETD** is often associated with high-frequency variations, is calculated by dividing the temporal noise (standard deviation from median signal with time) by the response (V/K).
- **Spatial NETD** indicating spatial uniformity, is derived from spatial noise (standard deviation of signal between neighboring pixels) divided by the response (V/K).

While temporal NETD typically correlates with shot noise indicative of high-frequency signal variations, spatial NETD is influenced by a combination of factors. These include material defects, fabrication non-uniformities, and low-frequency noise such as RTS and 1/f noise. In ideal scenario, the FPA performance is shot noise-dominated, and the spatial non uniformity is low thanks to a uniform fabrication process. However, low frequency noise mechanisms like 1/f noise or RTS, can compromise the sensitivity and image quality of the detector by manifesting flickering behavior in FPAs. This phenomenon is
characterized by low-frequency, sporadic signal fluctuations, impacting a few pixels [41].

To illustrate how the sensitivity of the FPA relies on the detector technology the NETD can be described with the photodiodes’ dark current and photocurrent under 3 assumptions [10,20,50]:

1. The variation of the current at the capacitor node is only determined by the high frequency shot noise $S_I = 2q(l_d + l_p)$.
2. The sensitivity limitation is given by a quadratic addition of the noise at pixel level and non-uniformities within the array ($u$).
3. The integration time $\tau_{int}$, is sufficiently low to prevent saturation of the capacitor well (N), $N > \tau_{int}(l_d + l_p)/q$.

$$\text{NETD} = \frac{1}{C} \sqrt{\frac{q}{\tau_{int} l_p} \left(1 + \frac{l_d}{l_p}\right) + u^2}$$

(15)

This expression suggests that independently of the scene contrast, the components which favor a low NETD (i.e high sensitivity) of the detector are: long integration time, high photocurrent, a low dark current to photocurrent ratio, and minimal non-uniformity at the array level.

However, the capacitor size and the desired frame rates limit the integration time, especially when detecting fast-moving objects in the scene. Increased photocurrent can be accomplished with faster optics but may add more volume to the cameras while improving the dark current to photocurrent ratio relies on lower operating temperatures.

These requirements translate to the detector array requirements, requiring high QE, low dark current, and uniform array processing while mitigating the low-frequency noise effects. Ultimately, the goal is to achieve an optimal NETD with slow optics, short integration times, and high operating temperatures.

**Modulation transfer function**

The MTF is the absolute value of the Fourier transform of the point-spread function (PSF). For an ideal FPA with pitch $d$, this corresponds to the Fourier transform of a square response of width $d$ [51]:

$$\text{MTF}_{FPA}(f) = \text{sinc} \left( \frac{f}{d} \right)$$

(16)
Where \( f \) is the spatial frequency. This expression defines the resolution of an ideal detector up to the Nyquist frequency \( f_N = 1/2d \); spatial variations above the Nyquist frequency are not resolved.

Figure 11 shows the MTF as a function of the spatial frequency for ideal detectors with pitches ranging from 30 to 5 \( \mu \)m and their corresponding \( f_N \). The figure also indicates the ideal value of the MTF at the Nyquist frequency, \( MTF_{id}(f_N) = 0.64 \). It is clear from Figure 11 that decreasing the pixel pitch increases the MTF and the range of spatial frequencies resolved by the system.

![Ideal MTF as a function of the image spatial frequency for 30, 15, 10, 7.5 and 5 \( \mu \)m pitch detectors.](image)

**Figure 11.** Ideal MTF as a function of the image spatial frequency for 30, 15, 10, 7.5 and 5 \( \mu \)m pitch detectors.

The real detector MTF, however, will depend on the interpixel cross talk as this phenomenon blurs the PSF [52]. Cross talk between unit cells in the ROIC is minimal, however, in the detector it can have two origins:

1. Electrical cross talk: Photo-generated carriers diffuse into adjacent pixels.
2. Optical cross talk: Photons diffract and end up absorbed in neighboring pixels.

The impact of crosstalk depends on the array architecture. IR detectors typically come in two formats: planar and delineated. Figure 12 depicts the device architecture for planar and delineated detectors and illustrates crosstalk mechanisms. Planar arrays suffer from both electrical and optical crosstalk. In contrast, delineated arrays electrically isolate pixels by etching trenches in the material, preventing electrical crosstalk. While this approach results in a close-
to-ideal MTF, it comes at the cost of increased processing complexity and reduced absorber volume in the pitch. **Article VI** presents an experimental and theoretical study of the MTF in fully delineated T2SL detectors.

![Cross-section diagram](image)

**Figure 12.** Cross-section diagram of the inter-pixel crosstalk mechanism for planar (a) and delineated (b) detector arrays.

Decreasing the pixel pitch in infrared imaging systems without inducing crosstalk is advantageous for improving the resolution of the FPA. However, it is crucial to account for the optics-induced diffraction effects in the imaging system's resolution as the optics, rather than the pixel pitch, often limit the detector's resolution.

The Airy diameter from diffraction limited optics is given by the Rayleigh criterion, \( \varnothing = 2.44 \lambda F \), which depends on the wavelength and the f-number \( (F) \). These parameters and the detector pitch define the boundaries of the detector and optics' limited resolution.

For \( F\lambda/d \leq 0.41 \) the resolution depends solely on the FPA as the Airy diameter is smaller or equal to the pitch size. For higher \( F\lambda/d \) the MTF of the system will also depend on the optics of the system.

Despite the influence of optics, state-of-the-art systems offer a degree of oversampling beyond the diffraction limit, with \( F\lambda/d \) between one and two, corresponding to 2.44 and 4.88 pixels per Airy diameter [53]. Advanced optics systems can offer resolution beyond the diffraction limit, and image processing software can correct diffraction-related effects.

### 2.4. IDDCA and cooler performance

The IR camera operates similarly to conventional cameras, creating visible representations of real scenes by detecting variations in the collected radiation. This process involves multiple optoelectronic stages: optics, detector, data
acquisition system, signal processing electronics, memory, software, and the display. The focus of this thesis is the detector, the core component that converts incoming light (photons) into an electric current. Figure 13 depicts the IR imager’s main components that interact with the photodiodes: the optics and the IDDCA.

![Figure 13](image)

**Figure 13.** Schematic illustration of the components of an IR imager that interact with the detector.

Sections 2.1 and 2.2 detailed the optical system's role, explaining the origin of radiation and how optics affect the radiation reaching the detector. This impacts the photodiode's signal and the system's overall dimensions.

On the other end, the FPA is housed within a dewar, cooled by a cryocooler to maintain the optimal temperature for IR detection. The packaged unit formed by detector the dewar and the cryocooler is the IDDCA (integrated detector dewar cooler assembly). The detectors' operating temperature directly influences the IDDCA’s size, weight, power, and cost [54]. Moreover, besides stationary performance metrics, the operating temperature significantly affects transient behaviors, such as the cooldown time, which dictates the time to operational state of the IR imaging system. Consequently, the specific operating conditions and application requirements determine the selection of a suitable cooler. The cooling technologies used for IR detectors are typically [54]:

- **Stirling Coolers:** which utilize the reversible Stirling cycle for cooling. They are reliable and come in two types - linear and rotary. Linear types are quieter and more reliable, while rotary types are smaller and more efficient. Notably, they come in split (separate compressor and cold finger units) and integral configurations (compact unit with both parts).
- **Pulse-Tube Coolers:** Like linear Stirling coolers but with no moving parts in the cold finger, leading to very low vibration levels. They are highly reliable, making them suitable for applications requiring extended operation
with minimal maintenance such as space observation. However, their larger size, weight, and power consumption can be a limitation.

- **Joule-Thomson Coolers**: Operate based on the cooling effect from the free expansion of gas. They are static, with minimal moving parts, and provide a fixed stable temperature. A limitation is the dependence on the volume of gas supply, which restricts the duration of the cooling phase.

- **Thermoelectric Coolers**: Based on the Peltier effect, these coolers are entirely static and suitable for applications requiring lower cooling temperatures (up to 200 K). They are compact but have lower efficiency compared to other types.

Each type has its specific advantages and limitations, making them suitable for different applications based on factors like size and weight, power consumption, reliability, ease of integration, vibration levels and cost. Table 2 shows a qualitative comparison between the different cooler types.

<table>
<thead>
<tr>
<th>Temperature Range [K]</th>
<th>Cooling mechanism</th>
<th>Type</th>
<th>Size and weight</th>
<th>Power</th>
<th>Integration</th>
<th>Vibration</th>
<th>Reliability</th>
<th>Lifetime</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>50-200</td>
<td>Cryogenic</td>
<td>Rotary Stirling</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>-</td>
<td>0</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Linear Stirling</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pulse - tube</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>++</td>
<td>++</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Joule Thomson</td>
<td>+</td>
<td>++</td>
<td>--</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>200-300</td>
<td>Peltier</td>
<td>Thermoelectric</td>
<td>++</td>
<td>--</td>
<td>--</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2.** Qualitative comparison of different cooling solutions from Ref. [54]

Table 2 indicates that the ideal option for miniaturization of the IDDCA is their assembly with a thermoelectric cooler. However, this thesis focuses on high sensitivity MWIR detection and therefore detectors require operating temperatures below 200K. For this purpose, at IRnova, IDDCAs are typically assembled with integral rotary Stirling coolers, chosen for their low SWaP benefits and ease of integration.

Nevertheless, there are different integral rotary Stirling cooler formats, and the extent of the miniaturization depends on the specific operating temperature.
within the cryogenic range. Figure 14 shows two IDDCAs with integral rotary Stirling coolers: one with a mini-cryocooler for cooling temperatures above 100 K, and another with a standard cooler for 80 K operation. Despite using the same cooler type, operating at 100 K instead of 80 K allows for a miniaturized cryocooler, significantly reducing the IDDCA’s size by two-thirds, and halving its weight and power consumption.

Figure 14. Picture of an IDDCA integrated with a standard integral rotary Stirling RM3 (left) and a RM31 mini-cryocooler (right) [55]

The operating temperature of the detector not only guides the selection of the cooler type and format but also impacts the power consumption and cooldown time of the IDDCA after its assembly. This is illustrated in Figure 15, with the evolution of the power consumption and cooldown time with cooling temperature of the FPA for IRnova’s IDDCAs cooled with a mini cryocooler system (RM31 from Thales [55]). The results indicate a decrease of 50% on both metrics as the cooling temperature is increased from 100 K to 150-160 K. Thus, the detector's operating temperature is a critical factor affecting every aspect of IR imagers, including the size, weight, power, and cost of the IDDCA.
Figure 15. Power consumption (a) and Cool down time (b) as a function of the detector temperature of an RMsl cooler integrated in an IDDCA. [54]
3. Experimental methods and techniques

This chapter outlines the experimental methods and techniques used during this thesis. As illustrated in Chapter 2, the activity at IRnova covers the entire value chain of detector manufacturing – from T2SL structure design to IDDCA assembly. This thesis focuses on developing the PDA fabrication process to improve the IDDCA performance, therefore, it required interaction with three different divisions within IRnova: research and development (R&D), production, and optronics.

The collaboration between these areas, on top of the ongoing fabrication and evaluation of existing IRnova products, set this thesis' framework. To navigate this complexity, the processing development was established in two stages:

- First, a dedicated R&D production line, consisting of single pixels and test samples, was established parallel to on-going production enabling a deeper analysis of the device performance.
- Secondly, using the standard IRnova workflow, fabrication and evaluation multi-wafer experimental batches were performed in collaboration with the production and optronics team to implement and validate the process improvements at FPA level.

Figure 16 illustrates the existing (grey) and implemented (blue) development workflow with the collaboration and task of the different divisions. The graph shows how this thesis reinforced IRnova’s development loop. In such a new setting, the production and optronics team benefited from the process development and characterization of the test samples. Moreover, the analysis and simulations from dedicated development samples provided a better understanding of the T2SL detector performance to the design team. At the same time this thesis benefited from the existing productions and characterization structure to materialize the development of into new detector formats.
It is worth noting, that in this collaborative environment, most of the PDA’s fan-outboards and FPA samples, together with all the FPA characterization, were conducted by the production and optronics teams, respectively. Moreover, the design team developed the surface leakage simulation software as it required modeling the detector structure using the T2SL electrical parameters. Figure 16 deliberately sets the T2SL wafers as the starting point for the process development, indicating that the design and growth of the T2SL structures are outside the scope of this thesis. Therefore, the experimental techniques used in this thesis cover all the steps from mask design and fabrication to characterization and simulation of test samples, single pixels, test arrays, and FPAs.

This chapter provides an overview of the fabrication methodology used and the characterization techniques needed to evaluate the detector material and to validate the fabrication steps. First, it describes the tools used to design the masks that determine the processing scheme of the manufactured devices. Secondly, it presents the fabrication sequence and the fabrication techniques employed across all sample types, from single pixels to FPAs and it lists the characterization techniques used to evaluate the fabrication process and assess the detector performance. Finally, it discusses the software used for the simulation part of the thesis.

3.1. Mask design – processing scheme

This thesis employed two CAD tools for designing masks, K-layout [56] and L-edit [57]. These tools facilitate the creation of hierarchical two-dimensional geometries for an efficient mask layout. IRnova already possessed masks for array fabrication and single pixels. However, developing the fabrication process and transitioning to smaller resolutions required iterating and complementing the existing masks. These programs were used to design each sample evaluated in
this thesis: single pixels (see example in Figure 17), PDA (for test arrays and FPAs), fan-out boards, and the MTF evaluation pattern.

The CAD design step establishes the fabrication sequence and device morphology, while during the fabrication stage certain aspects, such as dielectric thickness, metal stack composition, or etch depth are adjusted to the pixel design. Figure 17 shows an example of the mask set used for the fabrication of single pixels. Figure 17a illustrates the entire design with the full mask with an inset focusing on one of the mono elements, while Figure 17b shows the 3-mask conforming the fabrication process: mesa etch (red), the opening of the passivation (green) and the metal pattern (blue).

![Figure 17. Complete design (a) and mask set (b) used for single pixel fabrication including mesa etch (red), the opening of the passivation (green) and the metal pattern (blue).](image)

3.2. Fabrication techniques

This section illustrates the single pixel process and the fabrication and integration process of the fan-out board with a PDA fabrication, to exemplify the processing sequence of the samples used in this thesis. These two examples provide all the critical steps needed for understanding the morphology of the samples discussed and the main fabrication techniques used in this work.

*Single pixel process*

Figure 18 provides an overview of the standard single-pixel process, comprising the three masks shown in Figure 17. The process starts by depositing a resist or a dielectric layer onto the wafer containing the T2SL epi material, to cover the mesas during etching. The first mask provides the pattern with different photodiode mesa sizes for the etching of the T2SL material, followed by the deposition of dielectric layer that serves as passivation. A second mask is used to open the dielectric passivation at the top and bottom of the device. The final
mask defines where the metal will be deposited for biasing the photodiodes. The result is a structure ready for wire bonding and characterization.

<table>
<thead>
<tr>
<th>Resist / Dielectric layer deposition</th>
<th>Mask patterning, T2SL etching and dielectric passivation</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Resist / Dielectric layer deposition" /></td>
<td><img src="image2.png" alt="Mask patterning, T2SL etching and dielectric passivation" /></td>
</tr>
<tr>
<td>Dielectric etching</td>
<td>Metal deposition and wire bonding</td>
</tr>
<tr>
<td><img src="image3.png" alt="Dielectric etching" /></td>
<td><img src="image4.png" alt="Metal deposition and wire bonding" /></td>
</tr>
</tbody>
</table>

**Figure 18.** Fabrication sequence of single pixels.

The process scheme outlined in Figure 18 combined with a mask design with photodiode sizes ranging from 223 to 10 µm served for fabrication of single element photodiodes. These photodiodes were used for dark current characterization and the assessment of the surface leakage. In addition, to evaluate variations in pixel geometry, such as for introduction of two etch steps (described in chapter 5.2) or shallow etch (described in chapter 6.3), one additional mask was required during the etch phase.

While the geometry of the PDAs differs from this example, the fabrication sequence closely mirrors that of the single-pixel process. In the case of PDAs, the aim is to replicate the process in a grating format, with photodiodes separated by trenches, with pixel-to-pixel spacing matching the ROIC (Figure 19). These PDAs were used both as test arrays hybridized to fanout boards and for fabrication of FPAs when hybridized to ROICs.
Figure 19. Scanning electron microscopy images of a photodiode array with fully delineated pixels (PDA) and zoom in of one pixel in the PDA, highlighting the important fabrication steps: 1) trench etching, 2) sidewall passivation and (3) metallization.

Fan-out board fabrication and integration with a PDA

Figure 20 shows the processing scheme of the fan board and the hybridization process to a PDA. As in the single pixel fabrication process shown in Figure 20, each step corresponds to the stage of the sample for each mask layer. For simplicity, the illustration simplifies the detector side to the T2SL array structure, which should include the dielectric passivation and metal contacts resulting from the PDA production line.

The fanout board fabrication process uses a Si substrate and starts by patterning a metal layer and covering it with a dielectric. The metal pads will connect with the top and ground of the T2SL structure. The second mask patterns the dielectric layer with vias matching the PDA format and opens the areas for bump bonding. A third mask is employed for patterning an additional metal layer into the grating, setting the base for the In-bumps. With the Indium, the resulting structure is hybridized with the PDA. Following the hybridization, an underfiller material fills the gaps between the ROIC and the detector. The fabrication concludes by removing the substrate of the PDA and depositing an antireflective coating (ARC) to maximize light absorption in the photodiodes.
<table>
<thead>
<tr>
<th>Patterning off the dielectric layer</th>
<th>Metal deposition and patterning</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
</tr>
<tr>
<td>In bump formation</td>
<td>Hybridization with the PDA</td>
</tr>
<tr>
<td><img src="image3.png" alt="Diagram" /></td>
<td><img src="image4.png" alt="Diagram" /></td>
</tr>
<tr>
<td>Underfiller</td>
<td>Thinning down, ARC coating and</td>
</tr>
<tr>
<td><img src="image5.png" alt="Diagram" /></td>
<td>wire bonding</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 20.** Sequence of the fanout board fabrication and its integration with the PDA.

Two considerations emerge from the process scheme presented in Figure 20.

- **Leveling off the ground contact (GND):** The hybridization requires the PDA's ground contact to be at the same level as the top of the pixels. Therefore, the metal layer in the PDAs requires a specific patterning to bring the bottom contact of the pixels to the top of the T2SL structure.
- **Independence of In-Bump Position:** The hybridization process is independent of the In-bump position. Therefore, the Indium connectors can alternatively be deposited on the PDA side—as demonstrated later in this thesis.

During this work, the sequence outlined in Figure 20 is used for the fabrication of varying pitch PDAs and fanout boards which are then characterized. The same sequence is also applied for integrating the PDA with a ROIC (Figure 21). However, in the case of FPAs, the hybrid device is mounted on ceramics for
further packaging. Finally, for MTF evaluation, the samples are prepared by depositing an additional metal pattern on top of the ARC of the FPAs.

![Figure 21](image)

**Figure 21.** Scanning electron microscopy images of an FPA, highlighting the important fabrication steps: 4) hybridization, 5) underfiller and 6) thinning down and ARC deposition.

**Fabrication techniques**

The following fabrication techniques were used to develop and produce T2SL-based single pixels, test arrays and FPAs:

1. Etching processes to etch the dielectric and to define the photodiode pixel topography, include:
   a. Dry etching, i.e. Reactive ion etching (RIE), Inductively Coupled Plasma Etching (ICP RIE) and Ion beam etching (IBE).
   b. Wet etching, which is used to etch the detector material and remove the oxidation of exposed surfaces.
2. Dielectric layer deposition to cover the sidewalls of the pixels using different methodologies:
   a. Plasma enhanced chemical vapor deposition (PECVD)
   b. Atomic layer deposition (ALD)
3. Metal deposition serving as contacts to the pixels:
   a. Metal sputtering
   b. Thermal evaporation
4. Flip chip, chip-to-chip hybridization to connect the FPA with the ROIC.
5. Epoxy filling and baking to protect and secure the connections' mechanical stability.
6. Thinning down to remove the substrate from the FPA:
   a. Mechanical grinding
b. Chemical wet etch

For the patterning in all fabrication steps photolithography methods are used:

- Contact photolithography: Used for the patterning of masks in the production of single pixels.
- Projected photolithography: Used for the patterning of masks in the production of PDAs, ROICs, fanout boards.

3.3. Characterization techniques

The characterization techniques used in this research can be divided in two groups: 1/ techniques to monitor and evaluate the process development and fabrication of the samples and 2/ techniques to characterize the performance of the fabricated samples. The techniques used are listed below.

*Process monitoring techniques:*

- Thin film interferometry and spectroscopic ellipsometry to measure the dielectric layers thickness.
- Rutherford backscattering (RBS) to characterize the thickness and composition of the metal layers.
- Secondary Ion Mass Spectroscopy (SIMS) to monitor the IBE process.
- Optical endpoint spectroscopy (OES) to monitor the ICP-RIE process.
- Scanning electron microscopy (SEM), Focused ion beam (FIB) and Transmission electron microscopy (TEM) to image the fabricated samples.
- Energy dispersive x ray (EDX) and Time of flight elastic recoil analysis (ToF-ERDA) to characterize the chemical composition of the samples.

*Performance characterizations:*

- **Absorption:** determined using a Fourier transform infrared spectrometer. To measure the samples absorption involved measuring the transmission through the full epi stack and the substrate by etching away one side of a dedicated sample. The detectors’ absorption coefficient is extracted by correcting the absorber measurement with the substrate attenuation.
- **Responsivity:** determined using a dispersive spectrometer and an electrometer to bias the structure inside a cryostat. This process aims the photon flux through the sample's backside. A lock-in amplifier is used to minimize the noise and background signals, allowing for accurate QE extraction from the responsivity measurements.
• **Dark current**: measured using an electrometer with two approaches. The first uses a cryostat, where samples were shielded with a foil cap to block background thermal irradiation (i.e., dark conditions) and connections were established via wire bonding to metal pads. The second method employed direct probing in a cryoprobe station on top of the pixels at the expense of the samples being exposed to radiation from the measurement system (i.e., presence of background photonic current).

• **Noise**: The samples are loaded in a nitrogen bath and shielded with a foil cap to block background thermal irradiation. Noise spectrum is extracted basing the devices with an isolated low-noise voltage source, a transimpedance preamplifier to amplify the resulting noise current and spectrum analyzer that extracts frequency response of the signal. For shielding from external disturbances, coaxial cables and BNC connections are used throughout the system.

• **FPA evaluation**: Consist of acquiring a set of frame series taken in different illumination condition. The FPA illumination is achieved using an extended BB source through an aperture of a cold shield. By collecting the charge over specified integration time, each FPA frame presents digitized values of the signal on every pixel. For every pixel, these sets of frames are used to derive the time-average signal and the respective RMS noise. The relationship between the former and the illumination provides the optical response, which when combined with the RMS noise, results in the NETD.

The second part of the FPA evaluation focuses on its correctability – the ability to compensate for the variations in the pixels’ signal. This is obtained by applying the non-uniformity correction (NUC) to a selected signal frame and quantifying the residual inhomogeneity. It is common to use a simple 2-point NUC for this purpose, with the corrected target chosen between the correction points [58].

These two steps quantify the temporal and spatial components of the signal uncertainty over the array, thus providing the number of non-defective pixels.

### 3.4. Simulation software

IRnova already possessed custom-developed scripts tailored specifically to design and analyse the electro-optical performance of the detectors. However, these tools only solved the detector's performance in one dimension. Despite being useful for the design of the device structures, a one-dimensional simulation does not allow to account for the effects that might appear in an array format or when reducing the pixel size.
Therefore, this thesis employed commercial COMSOL Multiphysics software [58], which facilitates the creation of two and three-dimensional physics-based models. Two modules of COMSOL Multiphysics were used:

- Semiconductor Module [60]: Electrical modelling with a quasi 3D (2D axisymmetric with the Y rotational symmetric axis at the centre of the pixel) geometry was used to simulate the dark current and surface leakage degradation for a given fabrication process and pixel size. Used in Article II.
- Wave Optics Module [61]: Optical modelling with a 2D geometry (cross-section of the actual 3D detector array structure) was used to simulate the absorption, the optical crosstalk, and MTF for a given array geometry. Used in Article V and VI.

The developed models with these modules are extensively used to analyse the characterization results throughout the thesis. Moreover, besides deepening the understanding of T2SL devices, ultimately, the modelling effort targets creating a digital model of the physical devices (a digital twin) that can evaluate the design, fabrication process, and device geometry by simulations instead of experimentally, reducing the fabrication and development costs.
4. p-on-n p-type Sb-based type-II superlattice detector

Prior to the start of this thesis, in 2020, IRnova released a $640 \times 512 - 15 \, \mu m$ pitch full mid-wave detector integrated into a Mini-cryocooler IDDCA, making it the first European-manufactured SWaP T2SL detector, Oden MW [62,63]. The FPAs used a p-type Sb-based superlattice with a p-on-n detector structure (Figure 6a) to match the polarity of a direct injection ROIC and achieved a remarkable maximum operating temperature of 110 K.

The production of these detector arrays includes test arrays processed on the same wafer to evaluate and monitor the performance. Figure 22 shows the dark current measured for these test structures with varying pixel pitch from 225 to 10 \, \mu m. Figure 22a shows the bias dependence at 100 and 180 K, Figure 22b shows the P/A plot at the operating bias ($V_D = -0.1 \, V$) of the structure from 90 to 200 K, and Figure 22c shows the Arrhenius plot corresponding to the larger and the smaller devices for this temperature range at the operating bias. Additionally, Figure 22b includes the photocurrent density calculated from the QE measurements using F/5.5 optics and 300 K black body radiation and Figure 22c shows the activation energy fit of the current.

The dark current measurements show a spread of the J-V curves with a linear dependence on the perimeter-by-area ratio of the devices. This correlation suggests that the manufacturing process introduces surface leakage at the detector pixel sidewalls. The photocurrent level in Figure 22b illustrates how this surface leakage prevents the 15 \, \mu m pitch devices from operating at a higher temperature than 110 K. Moreover, Figure 22c indicates that despite the fact that surface leakage completely dominates the dark current density of small pixels, the mechanism behind this degradation is a GR and diffusion-activated current at low and high temperatures, respectively – a phenomenon which was not fully understood at that time.
The surface leakage restricted the use of the SWaP 640 × 512 format, 15 um pitch to 110 K operation for high-end imaging applications requiring a high photo-to-dark current ratio. Furthermore, despite the higher photocurrent expected from broader optics, the increase of surface leakage with decreasing pixel pitch hindered the development of high-resolution FPAs with pitch < 15 µm.

To mitigate surface leakage current in p-type p-on-n devices, a fabrication process was developed during this thesis, demonstrating potential gains of up to +30 K in the operating temperature.

Moreover, a quasi-3D model was developed to gain insight into the physical mechanisms behind the degradation caused by the mesa etch. This model calculates the total dark current density in the presence of defect traps at the
pixel sidewall and gives an excellent agreement with the measured dark current density for different temperatures, pixel sizes, and surface processes.

Part of this work is presented in Article II, where the surface leakage is studied experimentally and theoretically using single-pixel measurements and the simulation model. This chapter provides a broader study on this topic:

Firstly, it provides insight into the sidewall composition resulting from the different fabrication processes. Secondly, it complements the simulations from Article II and focuses on the bulk-surface relationship. Thirdly, it addresses the process development, evaluating the consistency of the reduced surface leakage fabrication process across different designs with varying cut-off wavelengths. Finally, the chapter presents the results of transferring the new passivation strategy to the 640 × 512 – 15 µm pitch detector format.

4.1. Passivation – sidewall composition

The differences in processing for the two samples discussed in Article II are stated in the text:

“From the epi-wafer, photodiodes with sizes ranging from 10 to 223 µm were fabricated by dry etching down to the bottom contact and passivated using a dielectric material. To study the surface leakage current, slight variations in the standard mesa etch processes\textsuperscript{43,44} have been applied to a different part of the wafer. After the dry etch, one part of the wafer was rinsed with a H\textsubscript{3}PO\textsubscript{4} solution\textsuperscript{43} (sample A), the other part was rinsed in deionized water (sample B). The process applied in sample A is the one used in the production of state-of-the-art 15 µm pitch full-midwave IR detectors, which have dark current densities lower than the photocurrent density up to 110 K, even with stringent light conditions of F/5.5 configuration.\textsuperscript{2} The process applied in sample B enables further reduction of the dark current density, thanks to lowering of the surface leakage component, and can potentially increase the operating temperature by 30 K for the small pitch HD detectors targeted in this study.”

However, it does not detail the exact composition of the sidewall resulting in the reduction of surface leakage. For the study of the sidewall composition, the samples corresponding to each process were analyzed by Energy-dispersive X-ray spectroscopy (EDX) on a transmission electron microscope (TEM) and by the time of flight-elastic recoiled detection analysis (ToF-ERDA).
The samples were prepared with a focus ion beam (FIB) on a scanning electron microscope (SEM) for the composition analysis. With this technique, a cross-section of the pixel was extracted from the substrate and polished to a thickness compatible with TEM. The resulting cross-section foil contained the interface of the pixel sidewall, which served as the region of interest for the composition analysis.

Next, the samples were mounted in the TEM and subjected to EDX analysis. Figure 23 shows the TEM images of the mounted samples with an inset on the pixel sidewall. The mounted sample corresponds to a pixel just after the dry etching process. Figure 23 illustrates the full pixel cross-section foil extracted with the FIB and the insets illustrates the different regions on the sidewall: at the top, the layered structure of the T2SL becomes apparent. The pure T2SL region is followed by an intermediate damaged region of T2SL intermixed with some other material, and finally covered by an amorphous layer.

The damaged region of the T2SL illustrates the impact from the etching process; this region is successfully represented as a trap density interface boundary in the simulation model. The appearance of the amorphous layer on the pixel sidewall was unexpected as it does not result from any sequential deposition process. The origin of this amorphous layer could potentially be attributed to either redeposition or amorphization of the etched species or even the potential role of further oxidation of the III-V species that occurred between the etching and the TEM analysis.

![Figure 23. TEM images of the pixel sidewall with different degrees of magnification.](image)
Figure 24 present the results of the EDX mapping conducted on the sidewalls resulting from each process. The mapping targets the In, As, Ga, Sb, O, and the dielectric on the sidewall (X). Figure 24a corresponds to Process A and is captured after the wet etching and the subsequent deposition of the dielectric layer. Figure 24b represents Process B and is taken immediately on a sample after the DI-water rinse. Therefore, the sidewalls contain the interface generating surface leakage in each case. In both figures, the T2SL absorber side is identified by the III-V components.

In Figure 24a, an oxygen layer extends into the T2SL structure beyond the dielectric layer despite the wet etching process. This phenomenon is attributed to the oxidation of the T2SL sidewall before deposition of the dielectric, leading to an altered composition of the T2SL sidewall. In the sample from Process B, the amorphous layer on the detector sidewall is found to be a dielectric, matching the composition of the hard mask used to cover the pixels during physical etching.

This layer will likely appear due to a redeposition process within the chamber during etching. Note that this redeposition process also affects the sidewall of the T2SL, as evidenced by the presence of an oxygen layer extending into the T2SL. The sidewall sealing phenomenon would reduce oxygen penetration and minimize
surface leakage. This process can be described as 'self-passivation,' as it occurs during the etching process within the vacuum environment of the reactive ion etching chamber. Despite the same dry etch process for both samples, the wet treatment removes the redeposited layer in Process A and exposes the sidewall to the cleanroom environment before the dielectric deposition.

The results from Figure 24 are consistent with existing literature, in which oxidation of the III-V components is pointed out as one of the main factors causing the surface leakage [64-70]. Moreover, the results demonstrate that the impact on the sidewall composition is not solely a result of wet treatment or passivation but also of the specific etching process. These observations highlight the sensitivity of the device performance to the mesa structure, as differences in the processing can lead to a significant improvement in the operating temperature (30 K in this case).

**ToF-ERDA**

The ToF-ERDA study aimed to confirm the chemical composition of the T2SL sidewall after the mesa etching and to validate the hypothesis of material redeposition. The analysis focused on two PDA samples featuring a 15 µm pitch grating with 2 µm etched trenches, reaching a depth of 5 µm: one treated solely with a DI-water rinse and the other subjected to the respective wet etch. Therefore, each sample corresponds to Process A and Process B from Article II.

Figure 25 shows the schematic evolution of the mesa structure during the sequence of the etching for the hypothesis under study. Figure 25a illustrates the array structure before the dry etching, Figure 25b, shows the structure after the mesa delineation with the resulting redeposited self-passivating layer on the sidewall and Figure 25c depicts the same structure after the wet treatment, highlighting the removal of the sidewall layer.

![Diagram of T2SL and Dielectric layers with etched trenches](image-url)
Figure 25. Schematic of the hypothetical evolution of the test structures during the mesa etch. Before dry etch (a), after the dry etch (b) and after the wet etch (c).

The ToF-ERDA analysis employed a 44 MeV $^{127}$I$^{10+}$ beam, with incoming and outgoing angles of 22.5° relative to the sample surface. The analysis captured recoiled ions, corresponding to a depth of 600 nm in the sample, thereby setting the limit for the depth profile of the extracted atomic content. Although the entire mesa etch is not analyzed, the study offers the chemical composition on a global scale (typically, the beam diameter is in the millimeter range) and requires less sample preparation, contrasting with the EDX study, which only analyzed a section of an individual pixel prepared with the FIB.

In this study, the chemical composition is determined from the energy and flight time data of the recoiled ions collected for the self-passivated and wet treated samples. In both samples the III-V components extend in the depth of the analysis (low energies and long time-off-flight) while the hard mask dielectric, will characterize the top layer, with its depth extension reflecting its distribution in both the top layer and sidewall of the pixels.

Figure 26 presents the atomic content versus depth extracted from the energy-time-of-flight data for both samples grouping the components corresponding to the T2SL and the dielectric, respectively. The analysis excludes the Sb data due to its mass proximity with the backscattered ion beam. This exclusion results in inaccurate representation of the atomic content of the III-V materials; however, it does not compromise the qualitative assessment of the presence of dielectric along the depth of the sample, i.e. the sidewalls.

In Figure 26a the top of the sample (200 to 300 nm) containing dielectric corresponds to the hard mask. Below this layer, the counting of In, Ga and As atoms increases, corresponding to the composition of the T2SL. However, the dielectric signal remains between 10% and 30%, indicating sidewall redeposition.

The increase of the dielectric counts along the T2SL depth suggests non-uniform sidewall layer thickness. In Figure 26b, after the wet etch, the hard mask layer is thinner (150 to 200 nm), and the dielectric on the T2SL depth (sidewall) drops to less than 15%. These results, consistent with FIB and TEM mapping and provide a qualitative indication of the presence and removal of hard mask.
dielectric from the sidewalls of the pixel layers after dry and wet etching, respectively.

![Atomic content profile](image)

**Figure 26.** Dielectric and T2SL grouping of the atomic content profile extracted from the ToF-ERDA data of the PDA after mesa etch (a) and after a subsequent wet etch (b).

### 4.2. Surface leakage simulations

The experimental section of Article II involved fabricating varying pixel sizes from 10 to 223 µm from the same wafer with two different passivation approaches. The fabricated pixels, therefore, had the same bulk dark current component with different surface components. The study of the measured dark current density as a function of temperature for the different pixel sizes enabled the development of a quasi-three-dimensional (3D) model to simulate surface leakage degradation. For a given bulk dark current density, the quasi-3D model used a donor-like trap-assisted recombination boundary at the sidewall of the pixel to simulate the material resulting from the mesa etch. The calculated dark current density resulted in excellent agreement with the measured dark current density for the different pixel sizes and surface processes.

The results confirmed the presence of surface leakage current, with a diffusion character at high temperature and GR character at low temperature. This degradation is illustrated to emanate from accumulation of minority carriers in the absorbers’ sidewall induced by the traps at the interface. This section will expand this study by presenting the simulation results of the intermediate pixel sizes and discussing how different bulk parameters influence the surface leakage current in the device.
Complementary simulations

Article II compares the calculated dark current against the experimental dark current for 10 and 223 µm device sizes with excellent agreement at any given temperature. The analysis focuses on the 223 and 10 µm sized devices to access the closest bulk- and surface-limited performance as these are the largest and smallest measured devices. However, for a fixed bulk and surface, the dark current density of any device geometry can be modelled by changing the simulation volume.

Figure 27 shows the measured and simulated dark current density for the 10, 28, 73, and 223 µm devices at 110 and 200 K together with the corresponding P/A plot for Process A and Process B. Overall, the J-V curves show an excellent agreement between the simulated and measured dark current density at high and low temperature for both processes. As mentioned in Article II, the discrepancies at low temperatures for Process B are attributed to the overlap of the bulk and surface SRH mechanism. The P/A plot with the entire data set of measured pixels demonstrates that the method presented in the manuscript works for the intermediate sizes strengthening the value of the model.
Figure 27. Measured (symbols) and simulated (solid lines) dark current density of (1) sample A and (2) sample B at (a) 110 K and (b) 200 K as a function of the applied bias and at (c) $V_D = -0.1$ V as a function of the perimeter by area ratio.

**Bulk-surface relationship**

Article II demonstrates that the origin of the surface leakage is based on the interplay between the bulk properties and the surface trap states. The article follows the classical approach for surface leakage study which uses the same bulk material and applies different passivation strategies. However, with the developed modeling a complementary approach for surface leakage evaluation emerges, which is to change the input simulation parameters of the bulk for a fixed surface characteristic (traps type and density) at the pixel sidewall.

This section presents the simulation results of two varying bulk parameters: the minority carrier lifetime (50, 100, 500 ns) and absorber doping ($1 \cdot 10^{15}$, $2 \cdot 10^{15}$, $4 \cdot 10^{15}$ cm$^{-3}$). The study discussed the simulated dark current density results at 110 K and 200 K for the 10 µm pixel from Process A, which is the case with the highest surface leakage current component. The bulk dark current density computed without traps at the surface is included for comparison.

To establish the comparison among all the lifetime-doping combinations the results are presented in two tables. Table 3 shows the lifetime comparison grouping the results with the same bulk doping, and Table 4 shows the doping comparison grouping the results with common lifetime. The temperature variation is an already studied phenomenon in Article II. The device and the bulk dark current density evolve with minority carrier concentration and the activation of different current mechanisms (diffusion over GR).
Table 3. Lifetime comparison: simulated dark current density of the bulk and 10 µm device at 110 K and 200 K for varying minority carrier lifetime (50, 100, 500 ns) and absorber doping level (1·10^{15}, 2·10^{15}, 4·10^{15} cm^{-3}) with a fixed trap density at the pixel sidewall.
The lifetime comparison shows that differences in the absorbers' minority carrier lifetime impact the bulk dark current density. This effect corresponds to a lower recombination rate by which a longer lifetime decreases the dark current density. However, it is worth noting that this effect does not translate on the device's dark current density, which remains higher and constant. This result suggests that at high and low temperatures (GR and diffusion regime), the dark current degradation due to surface leakage is associated with the surface carrier concentration and band bending rather than the carrier lifetime.

This result points to the decoupling of the device's dark current density level from the bulk lifetime and, therefore, from the material quality. This highlights the potential risk of compromising excellent material growth by a suboptimal surface treatment as a longer lifetime does not improve the device performance in the presence of surface leakage. Therefore, improvements in growth techniques must be matched by advancements in sidewall treatment to reduce the devices' dark current density. On the other hand, if surface limitations dominate, the insensitivity to bulk material quality can offer a potential advantage for industrial applications, ensuring uniform performance across different wafer growth batches.

For the doping dependence, the absorber doping level impacts both the device and the bulk dark current density. The higher the doping, the lower the dark current density. For the bulk, at 110 K, this is associated with spreading the depletion region into the absorber layer, for which a higher doping results in a lower thickness of the depletion region. At 200 K, the lower dark current density
is due to the inverse dependence of the diffusion current of the doping concentration (Equation 5).

To compare the dark current density of the 10 µm device one needs to account for the different bulk levels. The slope resulting from the P/A analysis (Equation 7) is not suitable for comparing devices with different bulk dark current density, as the contribution of \( \frac{P}{A} J_s \) on the total dark current depends on \( J_b \). Instead, the ratio between the small pixel and the bulk expresses the total current density relative to the bulk level and can be used to compare the degradation for different cases.

Table 5 shows the dark current degradation of the 10 µm device with respect to the bulk dark current density as a function of the doping concentration for the different lifetimes and temperatures at the operating bias of the structure (\( V_D = -0.1V \)).

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Lifetime (ns)</th>
<th>Bulk doping 1( \cdot )10(^{15})cm(^{-3} )</th>
<th>Bulk doping 2( \cdot )10(^{15})cm(^{-3} )</th>
<th>Bulk doping 4( \cdot )10(^{15})cm(^{-3} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>50</td>
<td>1.1( \cdot )10(^{2} )</td>
<td>3.3( \cdot )10(^{2} )</td>
<td>8.7( \cdot )10(^{2} )</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>2.1( \cdot )10(^{2} )</td>
<td>6.6( \cdot )10(^{2} )</td>
<td>1.7( \cdot )10(^{3} )</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>1.1( \cdot )10(^{3} )</td>
<td>3.4( \cdot )10(^{3} )</td>
<td>1.0( \cdot )10(^{4} )</td>
</tr>
<tr>
<td>200</td>
<td>50</td>
<td>3.1</td>
<td>3.6</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>5.1</td>
<td>6.2</td>
<td>7.8</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>2.2( \cdot )10(^{1} )</td>
<td>2.7( \cdot )10(^{1} )</td>
<td>3.6( \cdot )10(^{1} )</td>
</tr>
</tbody>
</table>

Table 5. Dark current density degradation of the simulated 10 um device at 110 and 200 K for varying minority carrier lifetime (50, 100, 500 ns) and absorber doping (1\( \cdot \)10\(^{15} \), 2\( \cdot \)10\(^{15} \), 4\( \cdot \)10\(^{15} \) cm\(^{-3} \)).

Table 5 shows that the higher the doping concentration, the higher the degradation of the current. This effect is attributed to the higher band bending as, for a constant donor-type trap density, the distortion on the minority carrier concentration will be higher for a highly doped p-type absorber. The lower degradation with temperature corresponds, partially, to the reduction of the band bending with temperature resulting from the increase minority carrier concentration. Finally, Table 5, shows that the longer lifetime results in a higher degradation, which illustrates the increased importance of surface processing with material quality.
4.3. Impact of absorber bandgap on surface leakage

Following Article II and the previous sections, the two passivation strategies are applied during the fabrication of detectors with varying cut-off wavelengths. This section thus experimentally studies surface leakage current with different bulk materials.

This study uses the IRnova standard full mid-wave p-on-n p-type Sb-based design, known from Article II, and exploits its tunability for shorter cut-off wavelengths. It presents a comparative analysis of mid-wave detectors, adjusting the cut-off wavelength to 5.2 µm for MW1, 4.3 µm for MW2, 3.4 µm for MW3.

The absorber’s doping levels were set for each design’s bandgap to $N_d$ cm$^{-3}$ for MW1, $2 \times N_d$ cm$^{-3}$ for MW2, and $4 \times N_d$ cm$^{-3}$ for MW3, respectively and the barrier structure was tuned correspondingly to achieve low dark current. Figure 28 shows the wavelength (a), temperature (b), and applied bias dependence of the QE for each design.

![Figure 28](image)

**Figure 28.** QE as a function of the wavelength (a), temperature (b) and applied bias (c) for MW1, MW2 and MW3.
Figure 28 shows a decrease in QE for MW2 and MW3 compared to MW1. This decrease is attributed to a poorer collection efficiency of the material, as the three designs have comparable absorption coefficients (Figure 8). Additionally, the observed differences in turn-on bias - notably higher for MW3 (-0.6V) and MW2 (-0.3V) compared to MW1's standard (-0.1V) - suggest the formation of electron blocking energy barrier introduced by small band offsets at the absorber's heterojunction with the collector.

For the electrical characterization, pixel sizes ranging from 225 to 10 µm were fabricated using processes A and B. However, the characterization of MW3 was limited to pixel sizes up to 75 µm. Consequently, this study will focus on pixel sizes from 75 to 10 µm.

Despite these constraints and the operating bias disparities, the importance of the evaluating the self-passivation on different designs and the potential of experimentally studying the interplay of the surface and the absorber highlights this comparison's relevance. To solve the disparities arising from using a mature IRnova design (MW1) and the shorted cut-off designs (MW2 and MW3), the dark current analysis will focus on the operating bias of each structure.

*Passivation effects on different detector designs*

The experimental approach is like the one described in Article II in which the same wafer (same growth and, therefore, same bulk dark current density) is used to fabricate single pixels with different surface passivation for each design.

Figure 29 displays the dark current density at the operating bias as a function of temperature for the three cases and both passivation approaches. The dark current density is shown for the 10 µm pixel, which exhibits the highest perimeter-to-area ratio and is, therefore, most susceptible to surface leakage. Figure 29 also includes the potential photocurrent density for the incident radiation of a 300 K black body, using an optical aperture of F5.5, calculated from the QE measurements of each design.

Figure 29 shows that Process B consistently yields lower dark current density than Process A. This reduction can be attributed to decreased surface leakage linked to the trap density at the pixel’s sidewalls. This result demonstrates the compatibility of self-passivation with different bandgaps and suggests that the three designs suffer from the same surface trap type.
Figure 29. Measured dark current as a function of the inverse temperature for the 10 µm device fabricated with Process A and Process B for the MW1 (a), MW2 (b) and MW3 (c).

The process improvement allows increasing the maximum operating temperature defined by the temperature at which $J_{\text{photo}} = J_{\text{dark}}$. For MW1, MW2, and MW3, the reduction in dark current results in operating temperature increments from 90 to 110 K, 110 to 120 K, and 110 to 150 K, respectively. Despite the differences in QE, the operating temperature increases with for the shorter cutoff wavelength due to the lower dark current density for larger bandgap materials.

Surface-Bulk relationship in different detector designs

For the design comparison the analysis below focuses on the samples fabricated by Process B as the lower surface leakage makes the bulk more relevant for the overall performance.
For each design, the dominating dark current mechanisms for larger (75 µm) and smaller detectors (10 µm) are identified by studying the temperature dependence of the dark current density at the corresponding operating bias. Figure 30 shows the Arrhenius plots of the dark current density and fits the bandgap (E_g) and half bandgap (1/2 E_g) activation energies (E_a) for each design. Figure 30 shows that the surface leakage degradation mechanism is common for all three designs, with a GR component at high temperature and a diffusion component at low temperature. The temperature at which the diffusion current overcomes the GR current is higher for a shorter cut-off wavelength due to the intrinsic carrier concentration dependence on the bandgap.

![Figure 30](image)

**Figure 30.** Measured dark current density at the operating bias of the larger and smaller sized diodes fabricated using Process B of MW3 (a) MW2 (b) and MW1 (c) as a function of the inverse temperature.

Next, without a bulk reference, the comparison uses the dark current density ratio between the 10 and 75 µm pixel to define the surface degradation for the
different designs. Figure 31 shows the dark current density degradation at the operating bias between the small and the big pixels as a function of temperature for each design.

The design comparison shows a higher degradation for MW3 compared to MW1 and MW2. This trend aligns with the previous section in which the higher doping has been associated with higher surface leakage degradation due to the higher band bending. The same phenomena could also explain why the MW3 design benefits the most from switching from Process A to Process B. However, it is only a partial explanation as MW1 has lower doping than MW2 and comparable surface degradation.

On the other hand, the temperature evolution in Figure 31 shows that for MW3, the degradation decreases with increasing temperature, a phenomenon discussed in Article II, when comparing the two processes. This is not as clear for the MW1 and MW2, which show more constant behavior with temperature. These results suggest that the trap's impact on the minority carrier concentration does not reduce with temperature. However, such a trend could have originated in the degradation calculation as there is no big difference in the perimeter by area ratio between large and small diodes, and MW1 and MW2 diodes fabricated with process B show minimal surface degradation.

![Figure 31.](image)

**Figure 31.** Dark current degradation at the operating bias of -0.1 V for MW1, -0.3 V for MW2 and -0.6 V for MW3 as a function of the temperature.

Unfortunately, variations in growth runs, doping levels, and operating biases limit the scope of the comparisons and disable a precise determination of the
relationship between trap characteristics and bandgap. Future research at IRnova will standardize doping across all structures, enabling a more detailed and informative analysis of these traps.

Despite the current limitations, the result suggests that shorter wavelength IR detectors are not immune to surface leakage issues even with the anticipated higher operating temperatures. This challenge may persist across all wavelengths, as ultimately, it depends on how pixel delineation affects the minority carrier distributions within the pixel volume. These insights underscore the importance of continued investigations on surface leakage, particularly with the advancement towards dual-color and dual-band detectors that incorporate multiple absorbers within a single growth stack.

4.4. Self-passivation for 640 × 512 – 15 µm pitch Focal Plane Arrays

The main goal of this thesis was to increase the operating temperature of T2SL infrared detectors with a fabrication process compatible with high-resolution detectors. The single pixel results have demonstrated that self-passivation in p-type p-on-n devices is a potential strategy to reduce surface leakage currents.

This section presents the results of transferring the self-passivation processing into the array configuration. First, as an intermediate step, the 640 × 512 – 15 µm pitch format is evaluated.

The self-passivation process was implemented in Oden's production line by selecting one wafer of a multi-wafer batch and processing it accordingly, leaving the others with the standard process for reference. After the passivation step, the experimental wafer followed the same process as the other wafers, ending with the hybridization of the FPAs.

Sampling of two self-passivated FPAs were analyzed in terms of temporal and spatial NETD with F/5.5 aperture and a 60 Hz frame rate at 110 K. Figure 32 shows the results of the response pixel map (a) and the temporal NETD histogram (b) for both FPAs. The response map is shown with a ±10 % contrast span over the median response, making the deviation pixels appear black or white in the image. The NETD histogram shows the distribution of the NETD values across to evaluating its uniformity. The pixel count is normalized to 1 and the gray and black plot shows the data in logarithmic and linear scale, respectively.

Both FPAs show a lot of deviating spots randomly scattered over the whole array. The inhomogeneous response maps indicate high dissimilarity between the
fabricated pixels which translates to spatial NETD in the range of 1000 mK. The broad distribution of the pixel's performance is what composes the NETD histogram's high-end tail.

The operability of the array is defined by labeling the pixels with deviating performance (non-operating pixels (NOPs)) with the following conditions:

- Response deviations $> \pm 10\%$ from the local median
- Temporal NETD $> 60$ mK
- Spatial NETD $> 40$ mK

Using this stringent criterion, the typical performance of Oden shows an operability above 99.8% with a temporal and spatial NETD of 22 and 5 mK, respectively. The operability of the two FPAs with self-passivation are below 70%. Therefore, the operation of the self-passivated FPAs was a failure due to the non-uniformity of the process.

![Figure 32. Map of the optical response at 110 K with a display contrast is $\pm 10\%$ from the median level (a) and NETD histogram of 640 x 512, 15 µm FPA using F/5.5 aperture and 60 Hz frame rate at 110 K the black histogram is plotted in linear scale while the gray histogram is plotted in log scale (b) for the 2 selfpassivated FPAs (1 and 2).](image-url)
An array sample prior to hybridization was analyzed in SEM to further investigate this problem. Figure 33 shows the SEM cross-section of the self-passivated array. Figure 33 shows the peeling of the protective dielectric layer deposited after the passivation. This phenomenon could be attributed to adhesion problems on the redeposited dielectric layer, as it is not observed in the standard array samples. The exposure of the pixels’ sidewall to further processing steps could be the reason behind the damage in some pixels and the corresponding nonuniformity of the array.

The layers deposited on the mesa structure in the array configuration experience stress due to the periodicity and aspect ratio of the trenches, making the adhesion to the sidewall critical for good uniformity. This effect was not anticipated on the single-pixel level as the samples have a more relaxed topography.

The performance results of the evaluated FPA suggest that the self-passivation approach is only a viable solution for the fabrication of FPA once further development achieves the mechanical stability of the deposited layers, ensuring uniformity across the wafer. These results, however, demonstrate the importance of uniformity in the array performance and highlight the processing challenges of transferring single-pixel results to the array format.

Figure 33. Cross-section SEM image of a self-passivated PDA prior to hybridization.
5. n-on-p p-type Sb-based type-II superlattice detector

The ultimate objective of the thesis was to design and fabricate a HD T2SL FPA capable of operating at elevated temperatures. This objective requires the photodiode array and matching ROIC. During the thesis period, a 1280 × 1024 n-on-p megapixel ROIC with a 7.5 µm pitch was available. Therefore, the detector structure used in the 640 × 512 FPAs with a p-type absorber was re-designed with an n-on-polarity (Figure 6b) for assembly into the FPA format.

Design for assembly (DFA) however can compromise the manufacturability of the detector array. Article III discusses the challenges associated with manufacturing n-on-p detector with p-type absorbers using the experimental result from single pixel fabrication. The high surface leakage resulting from the p-n junction exposure is pointed out as a critical factor compromising the performance of n-on-p devices. Nevertheless, two alternative device geometries, shallow-etched and two-step-etched architectures proved effective in mitigating the degradation due to surface leakage at a single pixel level.

This section aims to complement those results by utilizing the simulation modelling tool presented in Article II. First, the exposure of the p-n junction to the etch process will be discussed and secondly, the simulation model will be used to analyze the current reduction mechanism of the two-step-etch geometry. Finally, the chapter expands on the results of transferring the two-step-etch processing to the 1280 × 1024 – 7.5 µm pitch detector format.

5.1. Polarity – Impact of the etch exposure

This section investigates the relation between surface leakage and device polarity. This analysis builds upon the experimental results discussed in Article III, which studied the surface leakage in p-on-n and n-on-p devices. Article III highlights the impact of the p-n junction's position on the device during the etching process, confirming a phenomenon observed in other detector technologies: increased exposure of the p-n junction during the etching process results in higher surface leakage [71]. While experimental evidence supports this observation, the literature still lacks a theoretical explanation. However, applying the surface simulation model can further explore this hypothesis by varying the trap density across the absorber’s depth to compute dark current density with different surface conditions near the p-n junction.
Figure 34 illustrates the trap density as a function of the etch depth, z (indicated in the schematic in the inset in Figure 34) used in the three simulated scenarios under consideration:

- Case A: the trap density linearly decreases with absorber depth (z), linking sidewall degradation to the time the sidewall has been exposed during the etching process.
- Case B: maintains a constant trap density throughout the absorber’s depth, which is the approach followed in the previous simulations and will serve as the reference.
- Case C: represents the scenario in which trap density linearly increases with absorber depth, mimicking the conditions of a p-on-n structure, with the highest trap density far from the p-n junction.

![Graph showing trap density distribution](image)

**Figure 34.** Trap density distribution along the pixel etch depth for the 3 cases under study.

The dark current simulation uses the same capture cross-section of \( \sigma = 5 \cdot 10^{-13} \text{cm}^2 \) for all three cases and it is computed for 7.5 \( \mu \text{m} \) pitch pixel to match the format of the 1280 \( \times \) 1024 detector array from Article III. The bulk parameters used for the simulation correspond to the experimentally extracted values from the n-on-p detector material. Therefore, they differ slightly from the p-on-n bulk parameters used in the previous section. This difference, however, will not change the conclusions extracted from this exercise as it just sets the baseline for the studied cases.

Figure 35 shows the corresponding dark current densities and the bulk dark current density computed at 110 K and 200 K. The corresponding trap density
from Figure 35 is kept constant with temperature for simplicity. For all three simulated cases, at both high and low temperatures, the dark current density of the pixel degrades compared to the bulk. However, the position of the traps has a strong impact on the level of degradation. The highest degradation occurs when the trap density level is high close to the top of the pixel, i.e. close to the p-n junction, as shown by the simulations performed for 110 K operating temperatures. At 200 K, the level of the device's dark current density does not differ much between the cases.

![Figure 35](image)

**Figure 35.** Dark current density simulation at 110 and 200 K for a 7 µm pixel for the three cases under study together with the bulk level in black.

The differences between the high and low temperature regimes correspond to the different regions in the device volume that generate the current. At 110 K the dark current is dominated by a GR mechanism in the depletion region while at 200 K the current is activated by the diffusion mechanism in the entire absorber volume. This makes the diffusion current more insensitive to the trap distribution along the sidewall while the GR current is intrinsically linked to the characteristics in the vicinity of the pn junction.

This phenomenon would explain a higher GR contribution, reported in Article III, in n-on-p devices compared to p-on-n diodes. However, it does not explain the appearance of the drift surface leakage component on the n-on-p device. Further optimization of the simulation methodology is required to increase the trap density without encountering convergence problems or to include traps in the other layers of the device to account for the full path of the surface drift.
current. For now, this just illustrates the concept of higher surface degradation on exposed pn junctions.

To further illustrate the GR contribution, Figure 36 shows the recombination rate for each case at 110 K and $V_D=0.1$ V in the top micrometer of the exposed absorber. The recombination rate extracted from the simulation solution is calculated along an evaluation segment. For Figure 36, the recombination rate curves correspond to segments in the center and on the edge of the pixel. This choice illustrates the recombination rate in the bulk of the pixel (i.e., not influenced by the surface characteristics and, therefore, the same for all the cases) and at the surface.

The first observation is that the recombination rate is higher along the edge of the pixel than in the center of the device in all three cases (A-C). This increased recombination rate is linked to the GR surface leakage current, since a higher recombination rate results in a higher current and as the surface to volume ratio increases, the current emanating from this region will dominate over the bulk current from the central part of the pixel. The second observation is that the recombination rate increases when the trap density in the vicinity of the pn junction increases, which explains the resulting higher dark current density in Figure 35.

![Figure 36](image_url)

**Figure 36.** Recombination rate as a function of the absorber depth at 110 K and $V_D=0.1$ V in the center and depth along the pixel sidewall for the three cases under study.

Starting from the hypothesis that a prolonged exposure to the etching process leads to increased surface degradation [71], these simulations support the
experimental observation of higher surface leakage in devices where the pn junction is located at the top of the mesa and thereby is more exposed to the etching process. These results highlight the importance of the trap distribution with respect to the pn junction position and offer a partial explanation for the degradation of n-on-p devices with a p-type absorber observed in Article III. Moreover, these results point to the potential advantages of shallow etched devices as a shorter etching process not only reduces the amount of surface exposed but would result in less damaged sidewall. On the other hand, higher surface leakage is anticipated for structures requiring thicker absorbers such dual band detectors [72,73] as the surface quality may degrade with longer etching processes.

5.2. Geometry – Impact of the etch offset

This section investigates the surface leakage relationship with the device geometry. Article III introduces the two-step-etch geometry as an alternative method for fabricating n-on-p FPAs with low surface leakage and high MTF [74]. This section discusses the mechanisms behind the dark current density reduction in this geometry, employing the quasi-3D model for the dark current simulations of a 220 and 7 µm pixel. For IR detector photodiodes, this geometry, illustrated in Article III, was initially proposed to reduce surface leakage; however, this section discusses the performance of the etch offset on a big and small pixel for both scenarios with and without surface traps.

Simulations without surface leakage

Figure 37 shows the dark current density at 110 K and 200 K, computed for a 220 µm and a 7 µm pixel with a 2 µm offset between the two etch processes, alongside the bulk dark current density for reference. Figure 37a reveals that for the larger pixel, the two-step etch geometry has no substantial impact on the dark current density at either temperature. The same holds for the smaller pixel at 200 K (Figure 37b). However, at 110 K, the dark current density of the 7 µm device is lower than the bulk dark current density, especially at high reverse bias, where the GR component dominates the dark current.
Figure 37. Simulated dark current density at 110 K and 200 K for the big (a) and small (b) devices with an etch offset of 2 µm.

To illustrate this phenomenon, Figure 38 showcases the computed electric field distribution on the 7 µm n-on-p detector mesa structure with and without the two-step etching at $V_D=0.1$ V. The illustration displays the pixel as cylindrical devices because of the 2D axis symmetric geometry of the quasi-3D simulations. In Figure 38a for the single etch process, the electric field in the p-n junction spreads across the entire mesa width. However, with the two-step etching, the electric field is confined to a smaller volume defined by the offset between the two etch processes. This reduction in depletion region volume relative to the pixel volume leads to a decrease in the total GR dark current level.

Figure 38. Electric field distribution at $V_D=0.1$ V for the 7 µm n-on-p detector mesa structure with (a) and without (b) the etch offset.
The decoupling of the volume responsible for the GR from the pixel volume has a negligible impact on the 220 µm pixel, which is why the simulated device exhibits the same dark current density as the bulk. However, this difference becomes important for the 7 µm pixel, where 2 µm offset results in a significant reduction of the GR volume.

Figure 39 shows the simulation results of dark current density with varying etch offsets for the 7µm pitch pixel. The figure illustrates that as the etch offset increases, the reduction in G-R also increases, approaching near-diffusion-limited device performance across the entire bias range.

However, the practical extent to which one can reduce G-R depends on processing capabilities and hybridization requirements. This approach will be more effective in larger pitch formats by patterning a more significant difference between the top GR volume and the pixel volume.

![Figure 39](image.png)

**Figure 39.** Simulated dark current density at 110 K for a 7 µm device with varying etch offset.

Conceptually, this approach is the processing analogous to the barrier detector design [19]. In the barrier case, the depletion region is intentionally confined in a high bandgap layer, reducing the GR impact on the total current. In this case, the GR component is reduced by geometrically confining the depletion region within a smaller volume. This approach suggests that through appropriate processing, the contribution of GR dark current density can be reduced, resulting in near-diffusion-limited performance over a broader bias and temperature range. This strategy could be explored as an alternative approach to enhance the performance of T2SL devices in cases where optimal barrier layers are difficult to
achieve by growth as is the case in MOCVD-grown T2SL structures [15-18, 75-79].

*Simulations with surface leakage*

Next, the analysis of this geometry is conducted in the presence of surface leakage. The discussion compares larger and smaller pixels with surface traps to weigh the effects of a etch offset on the surface leakage. Figure 40 presents the simulated dark current density at 110 K and 200 K for a 220 µm and a 7 µm pixel with a 2 µm offset between the two-etch processes, along with the single etch step along with the bulk dark current density for comparison. For both sizes the surface trap density is set to $N_t = 5 \cdot 10^{10} cm^{-2}$ with a capture cross-section of $\sigma = 5 \cdot 10^{-13} cm^2$ at both 110 K and 200 K.

\[
\begin{align*}
\text{Figure 40.} & \quad \text{Simulated dark current density at 110 K and 200 K for the big (a) and small (b) devices with (dashed lines) and without (solid lines) an etch offset of 2 µm and a trap density recombination boundary on the absorber’s sidewall.} \\
\text{For the simple one-etch step, as observed in Article II, the absence of an etch offset leads to increased dark current density at both high and low temperatures. This manifests as additional GR and diffusion dark current density, with a more pronounced impact in the smaller pixel due to its higher surface-to-volume ratio.}
\end{align*}
\]

On the other hand, the 2-etch step geometry is demonstrated to reduce surface leakage for both the large and small pixels at 110 K and 200 K. However, the physical phenomena responsible for this reduction differ at high and low temperatures.
High Temperature Regime:

At 200 K, 7 µm and 220 µm devices experience dark current degradation due to diffusion surface leakage. Notably, this degradation originates at the absorber's edge, a consistent behavior for both the one etch step, and 2 etch step geometries. However, the 2-etch step devices exhibit less dark current degradation in this regime.

This improvement can be attributed to the partially reduced collection efficiency of surface carriers, as discussed in Ref. [74], where the extended path of surface carriers to the collection contact, extended by the etch offset, is pointed out as a reason for improved surface leakage.

It is worth noting that this phenomenon primarily affects carriers originating at the surface. In the simulations from Figure 37 (without surface traps), the device's dark current density in the diffusion regime equals that of the bulk at 200 K despite the etch offset. This suggests that the extended path argument mainly applies to surface carriers, implying that the 2-etch-step geometry will not compromise the collection of photocarriers absorbed within the pixel volume.

Low Temperature Regime:

At 110 K, the larger pixel exhibits the same dark current density as the bulk. This suggests that a 2 µm offset successfully mitigates the dark current degradation stemming from GR at the surface. On the other hand, the smaller pixel exhibits two phenomena: higher dark current density than the bulk at lower reverse bias and lower than the bulk at higher reverse bias. The latter results from the reduction in GR due to the confinement of the depletion region. The former is associated with diffusion surface leakage from the absorber's edge.

The reduction of GR surface leakage becomes apparent when comparing recombination along the 's edges. Figure 41 illustrates the recombination rate at 110 K and $V_D= 0.1$ V within the first micron of the exposed absorber, comparing the single etch and two-etch-step geometries to the center of the device. In the case of the two-etch-step geometry, surface recombination is negligible compared to the single etch or even the bulk.
This effect is analogous to edge termination structures used in power devices, where beveled geometries are implemented to adjust the electric field distribution of the pn-junction and relieve the surface from high electric fields [80]. In essence, it comes down to including a structural feature preventing the electric field from interacting with surface defects. This condition sets the lower limit for the etch offset required for successful surface leakage reduction.

In Article III, the hybridization requirements, and the small format of the target array (1280 × 1024 with 7.5 um pitch) limited the etch offset that one could implement. However, despite these limitations, by a wet etch, a beveled edge termination with an angle of -30° was demonstrated enough to control the surface leakage and enable an operating temperature of 100 K.

Figure 42 shows the result of the fabrication process with a SEM image of the cross-section of the detector before hybridization (Figure 42a) and the simulated electric field distribution at – 0.1 V corresponding to the device geometry (Figure 42b). Note that the curvature of the field lines near the beveled surface prevents the electric field from interacting with the absorber edge surface.
5.3. Etch offset for $1280 \times 1024 - 7.5 \mu$m pitch Focal Plane Arrays

The processing strategy for fabricating this detector format is detailed in Article III. Two alternative pixel geometries, shallow etch, and two-etch steps were demonstrated to reduce the surface leakage significantly. However, due to the small pitch in this detector format, only the two-step geometry was employed, given the anticipated crosstalk in the shallow etch geometry and its impact on the detector resolution.

Article III shows the dark current density after hybridization, demonstrating that introducing an etch offset in the array fabrication significantly reduced the surface leakage current. The reduction of at least three orders of magnitude compared to fully etched n-on-p devices suggested a potential operating temperature of 100 K when using an optical aperture of F/2.75.

However, during the measurement of the final FPA, a significant increase in dark current density was observed both in test diodes and in the overall measurements of the FPAs. The dark current density at different post-hybridization stages was measured to understand the root cause of the degradation of the finalized FPAs.

The post-hybridization steps are essential for packaging the detector into the IDDCA. Firstly, underfill is applied to fill the gaps between the ROIC and the detector using epoxy material. This step ensures a solid mechanical bond and protects the connections from stress due to thermal expansion mismatch between the silicon chip and the detector array. Following it, the detector is mounted onto
the ceramics, providing the base for the assembly and bonding. The final steps include grinding the substrate and depositing the ARC to maximize the light absorption in the pixels. While essential, the final productions stages can result in additional strain on the pixels, especially before substrate removal [81].

The origin of the dark current degradation was investigated by measuring the test diodes of an FPA in the different steps of the FPAs post-processing. Figure 43 shows the dark current density at 80 K for a test diode measured before and after the underfill step. Figure 43 reveals a significant increase of several orders of magnitude in dark current following the underfill step. This degradation resembles the dark current density measured in single deep-etched n-on-p devices, discussed in Article III. The observed result could be attributed to the strain induced in the pixels during the post-hybridization process suggesting that the patterned geometry on top of the pixel no longer prevents the surface electric field from degrading the total dark current density.

Figure 43. Measured dark current density of a test pixel before and after underfiller process.

Attempts to reduce the strain in the arrays by modifying the post-processing steps were performed but failed. The investigation concluded that the strain induced in the pixel array during hybridization is the leading cause of the increased surface leakage. The high sensitivity of the n-on-p design to the surface leakage and the pixel geometry makes the hybridization and assembly of these detectors very challenging, especially for the small pixel pitch used in these FPAs.
6. p-on-n n-type Sb-based type-II superlattice detector

This chapter reports the process development and performance of a mid-wave infrared detector using an n-type Sb-based superlattice absorber. As reported in Article II, the nature of the surface traps in III-V superlattices is donor type; therefore, the etching in the n-type absorber is anticipated to have less impact on the minority carrier distribution and the resulting dark current than in the p-type case [82,83]. This choice aligns with the design for manufacturing (DFM) principle, aiming to optimize the product's manufacturability by addressing potential issues during the design phase. Nevertheless, experimental results of surface leakage in III-V n-type structures have been reported, indicating that n-type structures are not exempt from surface problems under sub-optimal etch and passivation processes [71].

IRnova has developed an original n-type Sb-based superlattice structure which uses a p-on-n polarity (Figure 6c), for which its performance results are reported in Ref. [84]. This chapter will focus on the development of the etching and present the single-pixel results for different passivation and geometries for this structure. The single pixel results will be followed by the performance evaluation on an array format, first on a 640 × 512 – 15 µm detector format, then for a 10, 7.5 and 5 µm pitch test arrays and finally on a 1280 × 720 – 7.5 µm pitch FPA.

6.1. Etching process development

Despite the anticipated robustness of n-type structures, surface leakage can still degrade the dark current density on such devices if the etching or the passivation is inadequate [71]. This concern is accentuated in p-on-n structures, such as the one discussed in this chapter, where the junction lies in the most exposed region of the pixel. Additionally, the uniformity of the etch process is a critical industrialization factor as it will significantly influence FPA spatial uniformity and the wafer yield.

IRnova had already established a dry etch process for the p-type Sb-based structure before this thesis started that used a Cl-based plasma. However, a new etch process had to be developed for fabricating mesa devices on the n-type Sb-based design due to suboptimal profiles with the current composition and settings of the etching. This section shows the results of such process development.
The adjusted etch parameters included the chemical composition of the etching gas to allow for efficient byproduct removal and an optimal balance between chemical and physical etching. The total gas flow, to balance the residence time with the reactant abundance near the etched surface. The interplay between power and radio frequency (RF) to set the density of the ionized species in the plasma and the energy of the ions striking the surface. Finalizing with the process pressure to maximize the concentration of chemical species reaching the surface without inducing surface roughness or reducing the ions' striking energy by reducing the mean free path.

These parameters aimed to achieve the desired etch rate, high selectivity with the etch mask, no undercut, low surface roughness, and no faceting. Numerous iterations were evaluated by etching test structures and visualizing the etch profile results in the SEM. The resulting dry etching comprised a mix of chemical and physical process using Cl-based plasma, meeting the etching requirements on the n-type Sb-based material, as suggested by SEM images.

Figure 44a shows the profile of a test structure resulting from the prior etching process on the n-type design, and Figure 44b shows the results for the developed Cl-based etching.

![Figure 44](image)

**Figure 44.** SEM cross section image of the etched test structures with the prior (a) and optimized (b) Cl-based plasma process.

Figure 44a shows a damaged bottom surface, a rough sidewall, and redeposition of residues in the sample, making this process unsuitable for further FPA processing. On the other hand, Figure 44b shows that the sidewall and bottom surface are much cleaner with no byproducts left redeposited on the structure. The profile, however, is less straight than in the prior case suggesting a more chemical and, therefore, less anisotropic nature of the etch.
The final sidewall profile, however, must be evaluated using the detector array mesa pattern as the physics of the etch reaction may depend on the opened areas on the sample and the aspect ratio of the trench [85,86]. Therefore, additional testing of the developed process included patterning a 15 µm pitch grating on the n-type material. In this case, the dynamics of the etch process are closer to the FPA fabrication case. Figure 45 shows the results of etching down to the bottom contact with a 2 µm trench (Figure 45a) and 1 µm trench (Figure 45b) in the detector structure.

Figure 45 shows the complete delineation of the pixels of the pixels in both cases. The sidewall profiles are straighter than in the test structure from Figure 45b. The slight variation of the etch profile along the depth of the trench can be attributed to the different layers in the detector. Figure 45a shows the pixel's outer wall as the cleaving of the sample crosses the trench. In the 1 um trench sample, the cross-section corresponds to the center of a pixel. The etch tests demonstrate a very clean etch profile, indicating that the etch process has been successfully optimized and is ready for both single-pixel and FPA fabrication.

![Figure 45](image.png)

**Figure 45.** SEM cross section image of the developed Cl-based etch of the 2 µm (a) and 1 µm trench width.

### 6.2. Passivation – single pixels results

The etch process development evaluated the selectivity, etch rate, undercut, sidewall roughness, surface roughness, and faceting of the etched structures using SEM images. While the SEM analysis allows for identifying selectivity or uniformity issues and eliminating sub-optimal processes, it does not offer insight into the device's performance. Consequently, once the etch process reaches a visually satisfactory state, the evaluation must progress to include the fabrication and characterization of devices.
This section assesses the impact of the etch process on the device performance. The study compares the dark current density resulting from four single-pixel fabrication processes with sizes ranging from 10 to 223 µm, each employing a different passivation method for the exposed sidewalls. As in Article II, all samples share the same wafer for a common bulk dark current baseline. This evaluation aims to provide insights into the sensitivity of the n-type design in the fabrication process.

Table 6 describes the processing steps and differences in surface treatment for the various samples. The process aligns with that used in Article II, which is compatible with the manufacturing process of 640 × 512, 15 µm pitch FPAs to facilitate the potential integration into the production line. All samples underwent the same dry etch process using the optimized recipe down to the bottom contact; therefore, the devices are fully delineated. The first divergence is introduced in the wet etch pre-cleaning before dielectric passivation, with only Samples A and C undergoing this step, utilizing the same solution reported in Article II [87]. Subsequently, sample A and B and Sample C and D were passivated with different dielectric layers.

<table>
<thead>
<tr>
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<th>Sample A</th>
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Table 6. Processing sequence of the mesa sidewall for the four different samples.

Figure 46 shows the result of the dark current measurements at 130 K (a), 150 K (b), and 170 K (c) and as a function of the perimeter by area ratio of the devices for the four passivation approaches. The bias used for the comparison is \( V_D = -0.1 \) V, which is the operating bias of the structure, as demonstrated in Ref. [84]. Figure 46 shows no linear increasing dependence of the dark current density with reduced pixel size. This behavior is consistent in the entire temperature range and for the four samples, demonstrating a negligible contribution of the surface to the total current. Other variations in the graphs are attributed to scattering of the data associated with the fabrication and measurement of discrete single pixels.
Figure 46. Measured dark current density at \( V_D = -0.1 \) V as a function of the device’s perimeter by area ratio at 130 K (a), 150 K (b) and 170 K (c) for samples A, B, C and D.

The complete absence of surface leakage in the 13 \( \mu \)m devices enables higher operating temperatures of IR\textsuperscript{nova}’s 640 × 512 – 15 \( \mu \)m pitch detector format. Figure 47 presents the entire temperature dependence of the dark current density at the operating bias of the detector for all the samples. The dark current density is shown for the 13 \( \mu \)m device for all the cases except for sample A, where it was not possible to be measured, and alternatively, the 73 \( \mu \)m is shown; however, this does not compromise the comparison in the absence of surface leakage. The plot includes the diffusion current trend calculated for this design and the photocurrent level extracted from QE measurements and calculated for F/5.5 optical aperture in front of a 300 K black body. Figure 47 shows that all the samples show the same diffusion-limited behavior with a potential maximum operating temperature of 155 K, temperature at which the dark current equals the photonic current.
These results demonstrate the robustness of the n-type absorber design combined with the optimized dry etch process. Once the sidewalls are exposed, the subsequent processing has little or no effect on the dark current density level. This phenomenon arises from the DFM strategy that makes the minority carrier distribution on the device insensitive from the sidewall traps. These results fulfill the first objective of the thesis by evidencing the absence of surface leakage at a single pixel level.

6.3. Geometry – single pixel results

The design under discussion employs a p-on-n architecture, initially tailored for compatibility with the ROIC used for IRnova’s Oden MW detector. The p-on-n configuration, coupled with the n-type absorber, results in the placement of the junction on top, allowing for the adoption of shallow etch configuration or two-step-etch geometry. As previously discussed, the manufacturing process does not degrade the dark current density therefore the two-step etch geometry offers no advantage for surface leakage mitigation. However, the shallow etch configuration can be an alternative to maximize the fill factor of the detector array. A discussion on how fill factor compromises optical performance is available in Article V and Chapter VII.

This section presents the single-pixel results with a shallow etch geometry. The measured dark current on the shallow-etch devices serves to extract lateral diffusion length, employing the same methodology detailed in Article III. It is
important to note that while the extracted lateral diffusion length from the single-pixel results is a relevant physical parameter, the true measure of its significance lies in its impact on the real device performance, specifically on the resolution. This impact will be evaluated in the next chapter by characterizing the MTF of a shallow etched FPA.

As in Article III, the devices fabricated for this purpose are the circular ones to remove any contribution from the corners of the square pixels, with the pixels' diameter ranging from 223 to 10 µm. The mesa etch depth patterned the junction and extended through 18 to 25 % of the absorber's depth. Figure X shows the dark current density as a function of the applied bias for all the measured devices at 150 K, using the top area to calculate the dark current density. The inset in Figure 48 shows a cross section of the pixel geometry, indicating the additional current caused by lateral diffusion. Contrary to the previous section, the dark current density increases with reduced pixel size. Note that the level of the big pixels' current density is close to the level reported in Figure 48, while the small pixels have a current density an order of magnitude above. This excess in current originates from the lateral transport of carriers from outside the patterned area, which is more important in the case of small devices [71,88,89].

![Figure 48](image.png)

**Figure 48.** Dark current density at 150 K for the different pixel sizes. The inset illustrates the lateral contribution and the pixel size.

In Article III, the lateral diffusion length is derived under two assumptions: the absence of surface leakage and the total current being proportional to the area determined by the pixel diameter ($\rho$) and the lateral diffusion length ($L_\parallel$). Under the same assumptions, Figure 49 shows the extracted lateral diffusion length as
a function of temperature and bias. The inset in Figure 49 provides a schematic layout of a circular diode with an additional area created by \( L_\parallel \).

Figure 49 reveals that the extracted lateral contribution consistently exceeds 10 \( \mu m \). This length on both sides of the pixel is expected to significantly compromise resolution, as the signal collection boundaries of the pixels will exceed the pitch length in high pixel density FPAs (<15 \( \mu m \) pitch).

Furthermore, the extracted lateral diffusion increases with temperature, a behavior consistent with the higher mobility at higher temperatures. However, the fact that the diffusion length increases with temperature implies that the degradation in resolution will become more critical at the targeted operating regime for SWaP detectors as the electrical crosstalk is anticipated to increase.

![Figure 49](image)

**Figure 49.** Extracted lateral diffusion length as a function of the applied bias for temperatures ranging from 130 K up to 200 K.

Finally, the dependence on bias also demonstrates an increasing trend. This result is not related to a variation in the mobility and lifetime in the sample, which are intrinsic material parameters. However, it results from the underlying two-dimensional assumption of the extraction methodology, which attributes the excess current density to be proportional to the area determined by \( A = \pi \left( \frac{1}{2} \rho + L_\parallel \right)^2 \) [88].

This assumption does not consider variations in the collection efficiency along the depth of the absorber. However, in partially delineated diodes, the higher reverse bias increases the collection efficiency of lateral carriers by extending the depletion region further into the absorber [90]. The two-dimensional assumption
is a simplification that affects the evaluation of the extracted physical parameters. However, it gives relevant information from the device perspective, revealing the extent of the collection region covered by the shallow etch diodes.

6.4. 640 × 512 – 15 µm pitch Focal Plane Arrays

The single pixel results, described in section 6.2-6.3, demonstrated the n-type p-on-n detector structure to be an excellent candidate for high operating temperatures due to the absence of surface leakage. This section presents the results achieved when integrating the n-type Sb-based design into the production line of 640 × 512 – 15 µm pitch detector format. The integration of such design required the transfer of the mesa etch process developed for single pixels, while the remaining processing steps stayed consistent with the already established manufacturing process of Oden product. The array architecture for this case has a 2 µm fully delineated trench between pixels. Subsequently, the temporal and spatial NETD of the resulting 640 × 512, 15 µm pitch FPAs was evaluated utilizing an F/5.5 optical aperture and a 60 Hz frame rate.

Figure 50 shows the results of the NETD evaluation as a function of temperature for the first eight FPAs. It is worth noting that the temporal and spatial NETD values exhibited no significant variation with increasing temperature up to at least 140 K. Moreover, the median values for temporal and spatial NETD were approximately 21 mK and 6 mK, respectively, the same sensitivity as the previous Oden version but demonstrated at much higher temperatures [91]. The evaluation at even higher operating temperatures was not feasible due to limitations in the measurement setup available.
Figure 50. Temperature dependence of the temporal and spatial NETD values obtained with F/5.5 optics and 60 Hz frame rate of the eight fabricated FPAs.

To further illustrate the uniformity of the fabrication process, Figure 51 presents the optical response map with a 10% contrast (a) and the NETD histogram (b), measured at 140 K for one of the FPAs. Figure 51a shows a small number of deviating spots or clusters across the array, which translates to the narrow distribution of the histogram with only a few outliers. This FPA showed an operability of 99.84% at 140 K. These results underscore the robust performance and uniformity achieved across the array at 140 K.

Figure 51. Map of the optical response at 140 K. Display contrast is ±10% from the median level (a). NETD histogram of 640 x 512, 15 μm FPA using F/5.5 optical aperture and 60 Hz frame rate at 140 K (b). The black histogram is plotted in linear scale while the grey histogram is plotted in log scale.
The detector's maximum operating temperature comfortably supports its integration with the mini-cryocooler used in Oden's compact IDDCA. In addition, the increased sensitivity at higher temperatures has the advantage of lowering the power consumption compared to prior Oden versions [63].

To illustrate the stability of sensitivity across temperatures, Figure 52 presents a series of IR images captured at various operating temperatures. The images were taken by integrating one of the FPAs into an Oden IDDCA and employing an aperture of F/5.5, a frame rate of 60 Hz, and spectral response boundaries defined by the bandpass filter (3.7 - 5.1 µm). Figure 52 shows very high image quality resulting from the high MTF and low NETD up to 150 K. Beyond 150 K, a gradual increase in dark current density leads to the degradation in NETD. These results fulfill the second objective of the thesis by demonstrating the 150 K operating temperature of an IDDCA with a 15 µm pitch 640 × 512 FPA [91].

![IR images](image1)

**Figure 52.** IR images taken with the new generation of HOT T2SL detectors at IRnova at different detector temperatures. F/5.5 aperture, 60 Hz frame rate.

Finally, the IDDCA was integrated into a high-performance radiometric IR camera from Noxant with a reduced footprint [92]. The camera was also further integrated into a compact, lightweight, multi-spectral, long-range gyro-stabilized system by Trakka Systems [93]. Figure 53 shows a photograph of the Trakka Cam TC-300, and Figure 53 shows a snapshot of one of the videos taken with it.
Figure 53. Trakka Cam TC-300 (a) and image taken during the life demonstration (b).

6.5. Small pitch arrays

After increasing the operating temperature of the $640 \times 512 - 15 \, \mu m$ pitch detector format, the next objective was to reduce the pixel pitch. For that reason, the third goal of the thesis was to establish the potential for high operating temperatures in small pitch arrays. Unlike single pixels, the test arrays undergo a fabrication process more aligned with the FPAs. These arrays were processed on the same wafer during the FPA production batch but are hybridized to a fan-out chip. Consequently, their characterization does not require a matching ROIC. Like FPAs, after the hybridization, the substrate is removed, and an ARC is
deposited. These arrays are used for the dark current and QE measurement and to monitor the performance of the production batches.

The test arrays, with pixel pitches varying from 225 to 5 µm, were designed and fabricated in a 15 µm pitch 640 × 512 production batch, sharing wafers with both FPA and test arrays. Within this batch, a trench width of 1 µm were chosen for all structures. Figure 11 shows microscope image of the arrays with pitches of 15, 10, 7.5, and 5 µm.

Figure 54 illustrates how the reduction in pixel pitch results in increased pixel density, where the area of a 2×2 15 µm grating accommodates 9, 16, and 36 pixels with 10, 7.5, and 5 µm pitch, respectively. This straightforward geometric result bears significant implications for the fabrication yield and cost of IR detectors. For instance, considering the 15 µm pitch 640 × 512 detector format, a shift to 7.5 µm pitch would allow four times more FPAs to fit onto a wafer. Equivalently, one wafer could produce as many FPA chips as four wafers, leading to a substantial reduction in the cost per die [10,53,94].

![Optical microscope images of the 15, 10, 7.5 and 5 µm pitch PDAs.](image)

**Figure 54.** Optical microscope images of the 15, 10, 7.5 and 5 µm pitch PDAs.

Figure 55 presents the results of QE and dark current measurements post-fabrication for the 10 µm, 7.5 µm, and 5 µm pitch arrays. QE results are provided across a temperature range of 60 K to 160 K, while dark current data is shown for the temperature range of 120 K to 220 K due to the limitations of the measurement system. The data for both QE and dark current are presented at an operating bias of the structure \( V_D = -0.5 \) V. The dark current versus temperature plot includes the photocurrent level to illustrate the potential maximum operating temperature, calculated from experimental QE measurements at 150 K. This photocurrent corresponds to the radiation of a 300 K black body collected with F/4 optical aperture. The f-number is shown to be the same to compare the photocurrent density level however typically as the pitch is reduced so does the f-number.
Figure 55. Temperature dependence of the measured QE (top) and dark current density (bottom) at the operating bias of the detector (-0.5 V). The dark current plot includes the estimated photocurrent density for a 300 K BB and F/4 optics.

Figure 55 shows that the QE increases with temperature. This phenomenon is attributed to the increased diffusion length with temperature improving the collection efficiency of generated photo-carriers. However, the QE is shown not to increase and even exhibits a decrease with reduced pixel pitch, particularly in the 5 µm case. While not critical, these results deviate from the optical concentration phenomena discussed in Article V. This deviation can be attributed to two factors. Firstly, parameters such as metal coverage, sidewall profile, dielectric layers on the sidewalls, or even the presence of indium bumps could influence how light interacts with the array. Additionally in this case the arrays are fabricated with a 1 µm interpixel trench instead of 2 µm which minimizes the fill factor reduction and therefore the potential effect of the optical concentration. Moreover, the simulation model employed in Article V is a simplification, assuming perfect metal interfaces and straight sidewalls; further model development is needed to incorporate additional elements.

The second potential root cause for measurement discrepancies between arrays could be the measurement setup. Different alignments between the test structures might introduce variations in the calculated responsivity and therefore alter the QE extraction. Nevertheless, this trend will be further investigated as these where the first measurement results for such a small pitch.
Despite these variations, the extracted photocurrent levels, in combination with the measured dark current, consistently indicate a maximum operating temperature of 150 K for all structures. These results effectively demonstrate the high operating temperature potential in a small pitch array format successfully fulfilling the third objective of the thesis. Note that these arrays, being hybridized, differ from simple single-pixel structures and therefore their implementation into an FPA format requires only a matching ROIC.

This high operating temperature is only possible thanks to the absence of surface leakage in the dark current of the devices. To illustrate this phenomenon, Figure 56 shows the dark current density at the operating bias of the structure versus the P/A for the varying pitch sizes, from 225 to 5 µm. The graph includes the mean dark current density value at each temperature and shows that the dark current density does not significantly increase with the surface to volume ratio of the devices. This tendency is maintained across the entire range of temperatures.

It is worth noting that at lower temperature, the dark current density for the 7.5 and 5 µm pitch arrays is lower than that of the larger devices. This trend gradually corrects itself with increasing temperatures, reaching a point at 220 K where the smaller devices exhibit a higher dark current density than the 225 µm pitch array. This behavior may be attributed to the minority carrier concentration at the surface, particularly impacting the total dark current in the 7.5 and 5 µm pitch arrays (with mesa sizes of 6.5×6.5 µm² and 4×4 µm² devices), given their high surface-to-volume ratio. In this hypothesis, for the n-type absorber contrary to the p-type case, the mesa structure would deplete the surface from minority carriers instead of accumulating them and therefore, reducing rather than increasing the dark current density.

This would align with observations in Article II, where the distribution of minority carriers across the device volume and its evolution with temperature have been shown to determine the dependence of dark current density with pixel size. This phenomenon would be analogous to surface-induced effects in nanowires where the depletion region generated by the surface Fermi level pinning reduces the electrical area of the devices below its physical dimensions, impacting their performance in both dark and illuminated conditions [95]. However, more investigation needs to be carried out in this direction as for now no dark current simulation results could support this hypothesis.
Finally, the last objective of the thesis was to design and fabricate a high-definition (HD) T2SL FPA capable of operating at elevated temperatures. For that purpose and to integrate it using the n-type design a 1280 × 720 p-on-n 7.5 µm pitch ROIC was selected. Following the successful outcomes demonstrated with the test arrays, the p-on-n n-type design was chosen for this case. A 1 µm trench was selected for fabrication, in line with the test array design. Figure 14 illustrates the array fabrication results. Figure 57a displays a microscope image of a corner of the FPA, and Figure 57b presents a SEM image of the array before hybridization.

Figure 56. Temperature evolution of the measured dark current density as function of the perimeter/area ratio of the PDAs.

6.6. 1280 × 720 – 7.5 µm pitch Focal Plane Arrays

Figure 57. Top optical microscope image (a) and cross section SEM image (b) of the 7.5 µm pitch PDAs.
In this case, the same methodology employed in test arrays was implemented to evaluate the performance of the FPA before hybridizing to the ROIC. Consequently, parts of some FPAs were hybridized to a fan-out board for QE and dark current measurements after thinning down the substrate and depositing the ARC.

Figure 58 illustrates the temperature-dependent evolution of QE (a) and dark current density (b) at the operating bias of $V_D = -0.2$ V. Figure 58b includes the photonic current calculated from the measured QE for an optical aperture of F/2.8 at 140 K. Figure 58b shows that the dark current remains below the photonic current up to 155 K. Despite the different wafers used for this samples, hence the different optimal operating bias, the single pixels, the 640 × 512 – 15 µm pitch FPAs, an the 10, 7.5 and 5 µm pitch test arrays this design shows consistently maximum operating temperature around 150 K.

Figure 58. Temperature evolution of the measured QE (a) and dark current density (b) at the operating bias of the detector (-0.2 V). The dark current plot includes the extracted photocurrent density for a 300 K BB and F/2.8 optics.

Therefore, the 1280 × 720 – 7.5 µm pitch FPAs, like the previously discussed 640 × 512 – 15 µm, will support its integration with the mini-cryocooler used in Oden’s compact IDDCA. Such a detector will have the same size and power consumption assembly while producing HD-resolution images.

The results were achieved at the last stage of the thesis; however, Figure 59 shows a preliminary sample image taken with the 1280 × 720 – 7.5 µm pitch FPAs. The image was acquired by mounting the FPA in a test setup with an optical aperture of F/2.8.

Figure 59 shows a good image quality, demonstrating the high connectivity of the pixels after hybridization (>99.9 %). The FPA’s uniformity needs further
optimization as, for now, the ROIC-induced distortions affect its evaluation. Nevertheless, the preliminary results indicate the successful fabrication of 1280×720 format FPAs with 7.5 µm pitch.

Figure 59. Sample image acquired with a 1280 × 720 – 7.5 µm pitch FPA integrated in a test setup with F/2.8 optics.
7. Array geometry analysis

The preceding chapters focused on the analysis of the dark current density and the surface leakage contribution. Since the dark current density is intricately tied to device design, processing, and pixel geometry, the investigations focused on single pixels. However, other metrics that also determine the PDA performance such as the QE and the MTF depend additionally on the array geometry. This section discusses how the geometry of the array influences the absorption and crosstalk which, in turn, impact the QE and MTF, respectively.

7.1. Absorption and Quantum efficiency

This section discusses the QE of T2SL detector arrays, focusing on how the array geometry influences the optical response of the detector. Article V shows the QE to be independent of the fill factor in fully delineated arrays, indicating the potential of optical concentration to enhance the signal-to-noise ratio of the detectors. Article V uses the n-type Sb-based T2SL design due to its absence of surface leakage. This section expands that work by presenting experimental measurements on the p-type detector design, demonstrating that the optical concentration effect is not a particular case of one T2SL structure. Additionally, the simulation tool is employed to evaluate the optical concentration effect in 15, 10, 7.5 and 5µm pitch arrays, with varying trench width and incidence angles. This analysis aims to address the question about the limits of the optical concentration effect to enhance the signal-to-noise ratio of T2SL detector arrays.

Optical concentration in p-type Sb-based T2SL detector

Article V compares the pitch-QE and the pixel-QE derived from the backside illumination responsivity measurements at the operating bias for the different format n-type Sb-based T2SL photodiode arrays. The analysis contains fully delineated arrays varying from 225 to 10 µm pitch with a constant 2 µm trench, which results in a fill factor variation from 98 to 64%.

Analogously, the p-type Sb-based T2SL detector design results are presented in Figure 60 which shows the QE as a function of the wavelength. The results are shown at 120 K and at an operating bias of $V_D = -0.1$ V, which is the operating condition for the p-type T2SL design. Figure 60a shows that the pitch QE remains constant across the entire MWIR range despite the FF varying from 98% to 64% also for p-type T2SL detectors. These results indicate that optical concentration and its potential to increase the optical response (Figure 60b) is not a particular solution for one design. However, to increase the signal-to-noise ratio, it is
necessary that the dark current density does not increase when reducing the pixel pitch (and reducing the fill factor). As demonstrated in Article II and Article V, the surface leakage current increases with reduced pixel pitch in p-type superlattices but not in n-type superlattices (if proper processing conditions are applied). Therefore, only the n-type T2SL can take full advantage of this optical concentration effect in terms of enhanced signal-to-noise ratio.

![Graph A]

**Figure 60.** Pitch-QE (a) and pixel-QE (b) derived from the backside illumination responsivity measurements at 120 K and $V_D = -0.1$ V for the different arrays with varying pixel size.

**Complementary simulations optical concentration**

Article V demonstrates that the absorption in fully delineated arrays with a 2 µm trench separation between pixels structure is independent of the fill factor for pixel pitch down to 10 µm. This phenomenon translates to QE and results in a 50% increase in the photocurrent density in the small pitch arrays with a fill factor of 64%. However, the question is: To what extent does the photocurrent density increase by decreasing the fill factor and how sensitive the fully delineated geometry is to variations of the trench width? Moreover, since the optical concentration arises from the light-matter interaction, it makes the dependence of this phenomenon worth exploring for varying incidence angles, as smaller pitches typically require faster optics, which cover a broader range of incidence angles.

This section presents the simulation results to complement the results from Article V, focusing on small array pitches. For consistency, the simulations are based on the n-type design. Table 7 presents the spectral absorption for two varying geometrical parameters of the array: the pitch (15, 10, 7.5, and 5 µm) and the trench (2, 1, 0.5 µm). The simulated absorption spectra for the different
combinations are computed for a varying incidence angle of the light ranging from 0° (normal incidence) to 30°, which corresponds to the maximum incidence angle range of an optics with a F-number of one. The absorption coefficient and antireflective coating are the same as the ones used in Article V.

Table 7. Simulated absorption spectra for the 15, 10, 7.5 and 5 µm pitch fully delineated PDAs with 0.5, 1 and 2 µm trench and for an incidence angle ranging from 0 to 30°.

Table 7 shows that the incidence angle has little impact on the absorption spectra for the different geometries, and only minor spectral variations appear over the full MW spectral range. The minor variations are not critical since it is the integrated number of photons that sets the photocurrent level in the detector.
Therefore, these results demonstrate the optical concentration effect for various angles compatible with fast optics. This phenomenon results from the refractive index contrast mitigating the non-normal light incidence from the incoming medium (vacuum/air) to the structure's backside (n >1).

The trench comparison also shows a non-significant difference between the different array pitches, even for the most extreme case of the 5 µm pitch with a 2 µm trench. The absorption spectra suggest that QE will not scale down with the fill factor even for a fill factor as low as 36%, for which the optical concentration would represent a potential photocurrent density enhancement of \( \times2.8 \) compared to the planar configuration. This result aligns with the proposed implementation of photonic crystal structures in IR detectors, where the use of micro-hole and micro-pillar arrays has demonstrated the potential to reduce the fill factor to as low as 20%, further enhancing the SNR [96-98].

7.2. Cross talk and Modulation Transfer Function

This section discusses the MTF of T2SL detector arrays complementing the result from Article VI. Article VI uses the n-type Sb-based T2SL design and discusses theoretically and experimentally the impact of optical crosstalk in the resolution of detector arrays. Theoretically, a 2-dimensional model to simulate the spot scan profile is presented and used to compute the MTF as a function of the wavelength, the array geometry, and the incidence angle. Experimentally, the article evaluates the impact of the optical crosstalk on the MTF by the edge spread function method on fully delineated 15 µm pitch arrays. This section presents crosstalk simulations to give insight into the phenomena behind the MTF results. Secondly, it shows the MTF characterization results of delineated p-type Sb-based arrays. Finally, the electrical crosstalk is discussed using the edge spread function evaluation on a shallow etch n-type 15 µm pitch detector array.

**Optical crosstalk simulations**

As reported in the previous section and in Article V, the diffraction at the trenches has a positive effect on the detector performance as it results in optical concentration in the pixel. However, there is a difference between the total absorption of the array structure and how the absorption is shared between the pixels in the array. This is the topic of analysis of Article VI in which the impact of the optical cross talk on the detector MTF is studied for different array geometries.
MTF is a metric that describes the resolution of the array and, consequently, it is affected by interpixel crosstalk. Crosstalk is typically defined as the amount of signal that a pixel captures from radiation incident on its neighboring pixels. Pure crosstalk simulations may be more descriptive to illustrate the light-matter interaction dependencies on the array, and therefore, this section will complement the results from Article VI with them.

Experimentally, crosstalk measurements are performed by depositing a metal pattern on the backside of the detector. This metal pattern covers all the pixels except the center one, and cross talk is evaluated by measuring the response under the backside illumination of surrounding pixels compared to the illuminated pixel [99]. This experimental setup can be reproduced in the 2D optical simulation setup presented in Articles V and VI using a set of three pixels and the perfect reflective boundary condition as the cover metal. Figure 61 shows a schematic of the backside of the array after the mask deposition. The dashed line from Figure 61 indicates the cross-section used for the crosstalk simulations.

![Figure 61. Illustration of the backside mask for cross talk evaluation. The dashed line indicates the cross section that will be used for the crosstalk simulations.](image)

Crosstalk measurements are an excellent characterization tool in an array configuration since they account for both the electrical and optical crosstalk in the adjacent and diagonal pixels. In the simulation, only the optical component of the crosstalk in adjacent pixels is computed. However, this model is well suited for fully delineated T2SL detectors since there is no electrical crosstalk (because the pixels are physically electrically isolated), and the crosstalk in diagonal pixels is typically less critical than in adjacent pixels [100].

To illustrate the simulation, Figure 62 shows the electric field distribution for a 10 μm pitch with a 2 μm trench for an incident radiation with a wavelength of 4 μm and an angle of incidence of 15°. The limits of the electric field scale are set to illustrate the crosstalk in the adjacent pixels. Figure 62 shows how the backside...
metal prevents the incident radiation from propagating into the lateral pixels. However, the electric field corresponding to the central pixel extends towards the sides. The asymmetry between the two lateral pixels is due to the angle of incidence, which results in a non-symmetrical distribution of the leaked electric field. The presence of the electric field in the lateral pixels generates absorption in the neighboring pixel thus causing optical crosstalk and, therefore, compromises the resolution of the array.

**Figure 62.** Electric field distribution for a 10 µm pitch with a 2 µm trench for an incident radiation with a wavelength of 4 µm and an angle of incidence (α) of 15°.

To complement the result from Article VI, Table 8 presents the spectral crosstalk spectra calculated for varying array pitch (15, 10, 7.5, and 5 µm) and trench (2, 1, 0.5 µm). As for the MTF, the crosstalk simulation was performed with varying the incidence angle of the light ranging from 0° (normal incidence) to 30°. The absorption ratio between the adjacent and center pixels defines the crosstalk. For the tilted incidence, the crosstalk calculation uses the absorption in the pixel on the side along the light's propagation direction, making it the most affected side.
Table 8. Simulated optical crosstalk spectra for the 15, 10, 7.5 and 5 µm pitch fully delineated PDAs with 0.5, 1 and 2 µm trench and for an incidence angle ranging from 0 to 30°.

The spectral shape for the simulated crosstalk depends on the particularities of the light-matter interaction for each wavelength [51]; therefore, an explicit dependency does not manifest. For a clearer description, Figure 63 shows the total crosstalk by considering the cumulated absorption in the simulated spectral range. Figure 63 shows a general trend: as the incidence angle increases, the crosstalk increases, a behavior observed across all pitch and trench configurations.
This phenomenon is the reason behind the MTF degradation reported in Article VI.

On the other hand, the pitch comparison shows that as the pitch is reduced, the optical crosstalk increases due to the trench's increased importance on the total absorption of the pixel, which also agrees with the reduced MTF reported for smaller formats [101].

Finally, for the trench comparison, the simulations reveal an increased optical crosstalk for the broader trenches. This degradation is attributed to the radiation falling on the trench and, therefore, leaking to the neighboring pixels.

![Graph](image)

**Figure 63.** Cumulative crosstalk from 2.5 to 5.5 µm for the 15 10, 7.5 and 5 µm fully delineated PDAs with 0.5 (a) 1 (b) and 2 (c) µm trench as a function of the incidence angle.

The observed evolution of crosstalk with trench width may appear inconsistent with the findings in Article VI, where wider trenches led to higher resolution.
However, it is important to distinguish between the physical phenomenon of signal mixing (crosstalk) and the detectors’ ability to resolve object sharpness (MTF).

The MTF curves extracted in Article VI are affected by the crosstalk and the pixel size, not the pitch. Increasing the trench width results in smaller pixels and potentially higher resolution. Therefore, despite crosstalk simulations revealing an increased signal mixing with a broader trench, this effect is counterbalanced when considering the resolution of a smaller pixel.

The MTF’s dependence on pixel size explains why the MTF in a delineated array can exceed the ideal case at the Nyquist frequency. However, it is worth mentioning that this improvement is constrained to enhancing object sharpness up to the Nyquist frequency and not to increasing the Nyquist frequency itself, as the sampling spacing remains pitch-dependent [100].

**MTF measurement in p-type Sb-based T2SL detector**

Article VI compares experimentally the MTF of a 1 and 2 µm trench 15 µm pitch fully delineated n-type detectors. The MTF was derived by depositing a metal pattern on the two FPAs and extracting the edge spread function from the measured response under backside illumination. The average MTF at the Nyquist frequency was 0.60 ± 0.01 for the 1 µm trench and 0.61 ± 0.01 for the 2 µm trench. These values are very close to the ideal value of 0.64 and are also in excellent agreement with the simulation results.

Figure 64 shows the MTF curves along the x-axis and y-axis extracted using the same methodology for the 15 µm pitch p-type Sb-based T2SL detector design. The position of the pn junction in this detector format forces the structure to be fully delineated to electrically separate the pixel. Therefore, as in Article VI, the results reported for this case are only affected by optical crosstalk. However, only the 2 µm trench format was evaluated in this case.

Figure 64 demonstrates the uniformity and symmetry of the arrays with no differences between the MTF measured in the x and y-axis. The average MTF calculated with a 95% confidence interval is 0.62 ± 0.01. Again, this result is very close to the ideal value, indicating very low interpixel crosstalk resulting from the full definition of the array. The values are slightly higher than in the n-type case; this could be attributed to the position of the junction on the bottom of the pixel and, therefore, closer to the illuminated backside surface. However, the differences are minimal, considering that the differences in design also lead to different refractive index and absorption coefficients along the structure. Therefore, these
results just confirm the excellent array resolution achieved by fully delineating the pixels.

**Figure 64.** MTF calculated from the measured edge spread function in x- and y-directions compared to the ideal MTF of a 15 µm pitch detector.

*Electrical crosstalk in n-type Sb-based T2SL detector*

Numerous simulation studies have examined the MTF degradation in T2SL detectors caused by lateral transport. Typically, the reported MTF is significantly degraded compared to bulk materials, attributed to the anisotropic transport in T2SL \[102,103\]. However, there is a notable absence of published experimental results specifically addressing pixel sizes compatible with state-of-the-art T2SL FPAs.

For this reason, this section presents the experimental evaluation of a partially delineated 15 µm pitch FPA, following the methodology described in Article VI. In this case, the mesa etch only defines 25% of the absorber region, leaving the remaining 75% shared among the pixels comprising the array and, therefore, at the expense of electrical crosstalk.

Figure 65 illustrates the MTF curves along the x-axis and y-axis, together with the ideal MTF curve for a 15 µm array at the operating bias of the detector \(V_D = -0.3\) V. The average MTF in this scenario is notably lower, measuring \(0.3 \pm 0.01\) at the Nyquist frequency. This degradation is attributed to electrical crosstalk stemming from the lateral transport of photo-generated carriers, confirming the advice against planar or semi-planar array configuration using T2SL detectors. To exemplify the degradation, the measured resolution
corresponds roughly to the resolution of an ideal 22 µm pitch array, rendering the processing effort to increase the pixel density useless.

Figure 65. MTF calculated from the measured edge spread function in x- and y- directions compared to the ideal MTF of a 15 µm pitch detector.

This result complements the findings from the previous chapter, where the lateral diffusion length for the n-type detector structure was extracted. In this case, the lateral contribution can also be extracted by assuming the absence of optical crosstalk and attributing all deviations from the ideal MTF to electrical crosstalk. This assumption is valid, given the low levels of optical crosstalk observed for the 15 µm pitch format and the absence of a fully delineated trench. Utilizing the expression reported in [101]:

\[
MTF_{Detector} = MTF_{id} \times MTF_{crosstalk}
\]

\[
MTF_{crosstalk} = \frac{1}{1 + (2\pi L_{eff} f)^2}
\]

where the effective lateral diffusion length \(L_{eff}\) defines the crosstalk factor. Using equation 1 on the MTF data yields an extracted lateral diffusion length of 6.2 µm ± 0.72. This value is notably lower than the one obtained using the single-pixel results. The disparity arises from the architectural differences between the two devices. In the single-pixel configuration, the shallow etch result in a partially delineated mono element that collects signals from all the surrounding absorber volume. However, in the array case, each pixel's ability to accumulate signal is constrained by the neighboring pixels. As a result, the lateral contribution does
not manifest as a higher dark current density but rather as a redistribution of the current, leading to a reduction in MTF.

Therefore, the crosstalk anticipated from the evaluation of the lateral diffusion length in single pixels tends to be overestimated, as in array configurations the MTF degrades, but not to the extent implied by lateral transport properties. This phenomenon is exploited in planar array geometry to mitigate the degradation of MTF [104]. Moreover, while increasing the biasing does not alter the material properties, it has been reported to help mitigating the influence of the electrical crosstalk on the resolution in planar detectors [104]. Figure 66 shows the evolution of the MTF and the extracted effective lateral diffusion length curves with varying bias, ranging from 0.1 to -0.6 V. In Figure 66a, all the MTF curves extracted from the deposited pattern are superimposed, with the color bar indicating the bias for each curve. An increase in MTF levels is observed with the reverse bias of the FPA, reaching values of up to 0.35 ± 0.01 at -0.6 V. The improvement is primarily due to the enhanced efficiency of diode collection in partially delineated diodes.

![Figure 66](image)

**Figure 66.** MTF calculated from the measured edge spread function compared to the ideal MTF of a 15 µm pitch detector (a) and extracted effective lateral diffusion length (b) as a function of reverse bias.

The effective lateral diffusion also reflects this trend, reducing to below 5 µm at -0.6 V. This contrasts with the findings from individual pixel measurements (Section 6.4), where lateral diffusion length increased with reverse bias. The difference stems from the expansion of the depletion region in the absorber material, having varying effects depending on the sample configuration. In individual pixels, high reverse bias leads to increased current collection, resulting in a longer extracted lateral diffusion length. On the other hand, in the array
format, this expansion restricts the movement of carriers to adjacent pixels, thereby sharpening pixel transitions and enhancing the resolution. Nevertheless, despite these improvements, the MTF in the partially delineated detector remains far from the resolution capabilities demonstrated in fully delineated cases.
8. Conclusions and outlook

This thesis aimed to improve the manufacturing process of T2SL arrays to increase the operating temperature and resolution of IRnova's T2SL detectors. Such an investigation has resulted in a more profound understanding of the devices and achieved performance levels that push the state of the art of T2SL detectors.

Moreover, the implementation of such developments in IRnova's industrial-scale production has led to the demonstration of 640 × 512 − 15 µm format FPA, 10, 7.5, and 5 µm pitch test arrays and HD 7.5 µm pitch FPAs, all with the capability to operate at 150 K. Such milestones fulfill the thesis goals and significantly advance the industrialization level of T2SL detectors in Europe.

This chapter closes the manuscript by presenting the conclusion from the different studies launched during this thesis and gives an outlook on the technology.

8.1. Conclusions

The conclusions are divided into the four-performance metrics evaluated during this thesis:

*Noise - Article I*

**Temperature and bias dependence:** The 1/f noise coefficients for p-type Sb-based detectors have been extracted for the dark current PSD measurement of p-type Sb-based superlattices. The correlation shows that the 1/f component is linearly dependent on the tunneling current and has a square dependence on the GR and diffusion mechanisms. The noise coefficients are: $\alpha_{\text{GR}} = 4.8 \times 10^{-9}$ Hz$^{-1}$, $\alpha_{\text{diff}} = 1.9 \times 10^{-10}$ Hz$^{-1}$, and $\alpha_{\text{tun}} = 2.1 \times 10^{-16}$ AH$^{-1}$. With such low noise coefficients at 77 and 100 K, the shot noise dominates the noise spectra with corner frequencies of 7 and 10 Hz, respectively, while higher 1/f corner frequencies of 780 Hz and 2.1 kHz are measured at 125 and 140 K.

**Dark current (surface leakage) - Article II, III, IV and Chapter 4,5,6**

**Impact of Surface Passivation:** The studies have shown that surface passivation significantly influences the dark current's GR and diffusion components in double heterostructure MWIR p-type Sb-based T2SL detectors. The self-passivation process has been demonstrated to reduce surface leakage due to lower oxidation of the pixels’ sidewalls, regardless of the detector bandgap.
Nevertheless, such process has been demonstrated not to be uniform for optimal array performance.

**Surface passivation modelling:** A novel quasi-3D model to simulate the dark current of a device with surface leakage has been developed and validated against experimental data, demonstrating excellent agreement across different pixel sizes, surface processes and temperatures. This model successfully captures the effects of surface leakage current, characterized by the minority carrier distribution across the absorber volume. The importance of this model lies in its ability to evaluate fabrication processes and device geometries through simulation rather than costly experimental methods, thereby streamlining the development of T2SL photodetectors.

**Dependence on Detector Polarity and Photodiode Geometry:** Experimental observations indicate that n-on-p fully etched devices exhibit higher dark current degradation than their p-on-n counterparts, primarily due to additional GR and drift surface leakage components. This increased surface degradation in n-on-p devices has been quantitatively modeled by linking the surface trap density to the exposure time during etching. Shallow-etched and two-step-etched geometries have shown promise in reducing current density in n-on-p devices. However, the shallow etch geometry is anticipated to have degraded MTF and the two-etch-step has been demonstrated very sensitive to the post-hybridization fabrication steps in small-pitch FPAs.

**Design for manufacturing:** Due to the nature of the surface traps in III-V superlattices being donor type, DFM detector structures with an n-type absorber have proven successful in eliminating surface leakage. The design and the developed dry etching process result in detector devices without surface leakage, regardless of the subsequent passivation. Implementing such development into the production line has increased the operating temperature and resolution of IRnova’s detectors.

**QE - Article V and Chapter 7**

**Dependence on the array geometry:** Experimental and theoretical findings reveal that contrary to the Bruggeman and proportionality models, the QE in fully delineated T2SL detector arrays is largely independent of the FF. This independence is demonstrated in detectors with varying pixel pitches, where the absorption remains consistent despite changes to the radiations’ incidence angles and the arrays’ trench widths. The fully delineated array geometry has been found to concentrate the light within the pixel area like a photon-trapping geometry.
In the absence of surface leakage, the optical concentration contributes to an improved SNR, especially in smaller pitch arrays. Notably, the photocurrent density has demonstrated experimentally to increase by 50% in 10 \( \mu \text{m} \) pitch arrays.

**MTF - Article VI and Chapter 7**

**Dependence on the design and array geometry:** The impact of array geometry on the MTF of T2SL MWIR detectors has been evaluated through experimental and theoretical methods. Experimental results highlight that fully delineated 15 \( \mu \text{m} \) pitch arrays, free from electrical crosstalk, exhibit excellent MTF values above 0.6 at the Nyquist frequency regardless of the trench width (1 and 2 \( \mu \text{m} \)) and the detector design (n-type and p-type). In contrast, shallow etch 15 \( \mu \text{m} \) pitch arrays show significant MTF degradation, underscoring the superiority of fully delineated designs.

**MTF and optical crosstalk modeling:** The theoretical model developed to simulate optical crosstalk and MTF in fully delineated arrays aligns well with experimental data, and points to increased optical crosstalk in arrays with smaller pitches and broader trenches, especially at higher incidence angles. Nevertheless, these arrays maintain superior performance to the classical planar detectors. This model is an effective tool for evaluating different detector designs and array geometries, offering an alternative to experimental methods requiring sacrificial FPAs.

**8.2. Outlook**

The development of T2SL IR detector imaging assemblies presents a high technological complexity. The cover and first figure of this thesis displays such complexity in four main development areas: design, growth, fabrication, and integration. This thesis centres on the fabrication, and despite each branch's unique focus, all four share the same objective: maximize the information extraction from the IR scene in the most efficient way.

Significant advancements in single-band MWIR detectors have been achieved for the design, demonstrating a maturity level suitable for industrial-scale production, evidenced by the progress at IRnova between 2020 and 2024. Nevertheless, the versatility of T2SL designs in the LWIR and eSWIR regions offers further potential to expand into more application areas where T2SL could provide significant advantages compared to currently used technology. Moreover, increasing the design's complexity will allow for adding functionalities at the pixel level, such as dual-band detection.
In terms of growth, the efforts concentrate on reducing material cost per square centimetre by increasing the substrate diameter. Efforts are pushing towards the use of the largest available GaSb substrates and exploring MOCVD growth alongside virtual substrate techniques with GaAs and Si to achieve even larger wafer sizes and further reduce the cost.

The capability of the T2SL technology to move towards small pixel pitch and HD detectors with high operating temperatures has led to the development of high-resolution ROICs and more efficient coolers, minimizing the system SWaP. On top of that, the miniaturization endeavour pursues the reduction of the IR camera footprint by using compact optical systems and electronics.

Detector fabrication emerges as a key element in enabling the advancement of infrared technology. The processing complexity will escalate as the move towards higher resolution and more complex detector structures continues. However, in this context, the goal of processing should extend beyond preserving the design's original characteristics towards enhancing its overall performance. Elements such as optical concentration structures, plasmonic gratings, alternative pixel geometries, or specific array configurations will be instrumental in maximizing next-generation detectors' SNR and resolution attributes.

This thesis explored detector processing within the T2SL MWIR framework. Nevertheless, the methodologies and analyses presented—from detailed surface leakage study to pixel and array geometries evaluation—provide valuable tools for continuously advancing the detector technology.
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