# Development of IR Imaging at IRnova

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## ABSTRACT

Historically IRnova has exclusively been a company, focused on manufacturing of QWIP detectors. Nowadays, besides continuous improvements of the performance of QWIP FPAs and development of new formats IRnova is involved in development of QWIP detectors for special applications and has started the development of the next generation infrared detectors, as well.

In the light of the development of new formats we validate experimentally theoretical calculations of the response of QWIPs for smaller pixel size. These results allow for the development of high performance megapixel QWIP FPA that exhibit the high uniformity and operability QWIP detectors are known for. QWIP is also being considered for space applications. The requirements on dark current and operating temperature are however much more stringent as compared to the terrestrial applications. We show ways to improve the material quality with as a result a higher detector operating temperature.

IRnova is also looking at antimony-based strained superlattice material for the LWIR region together with partners at the IMAGIC centre of excellence. One of the ways to overcome the problem with surface currents is passivating overgrowth. We will report the status and results of overgrowing the detector mesas with AlGa(As)Sb in a MOVPE system. At the same centre of excellence a novel material concept is being developed for LWIR detection. This new material contains a superlattice of vertically aligned and electronically coupled InAs and GaSb quantum dots. Simulations show that it should be possible to have LWIR detection in this material. We will present the current status and report results in this research.

**Keywords:** QWIP, Infrared detectors, quantum well, dark current, type II superlattice, LWIR, MWIR, MOVPE

## 1 INTRODUCTION

IRnova is a company developing and producing infrared detectors, with focus on QWIPs. QWIPs, based on the mature III/V material system (Al)GaAs have shown very good uniformity and operability properties. In this work a review of the current status of infrared detectors at IRnova is presented, the QWIP technology is pushed to its limits, smaller pixel size, new formats and better material quality to reach higher operating temperature for space applications. Furthermore IRnova is also looking at antimony-based materials to overcome the limits of QWIPs: e.g. low operating temperature and relative low quantum efficiency.

## 2 SMALLER PIXEL SIZE

The trend for FPAs (Focal Plane Arrays) is towards smaller pixels, this can either be used to decrease the FPA size and thus the system cost or to increase the number of pixels, resulting in either better detection range or better situation awareness (same detection range, but bigger field of view). One of the main obstacles for smaller pixels in QWIPs is the light coupling into the pixel, which is crucial for QWIPs because of its polarization sensitivity of absorption. This is normally accomplished with a 2D grating converting the normally incident light into absorbable state [1]-[3]. The grating however, becomes less effective for smaller pixels, simply because fewer grating dots fit on one pixel. We have earlier reported on the result of a full 3D finite element simulation [4], these simulation results are here experimentally verified.

A wafer with a standard LWIR QWIP structure was processed to form pixels with the following size and grating parameters:

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Table 1 Mesas with different pitch and size

| Detector pitch [µm] | Mesas size [µm] | Number of grating dots per pixel |
|---|---|---|
| 15 | 13.7 | 4x4 |
| 17 | 15.7 | 5x5 |
| 19 | 17.7 | 5x5 |
| 20 | 18.7 | 6x6 |
| 25 | 23.7 | 8x8 |
| 30 | 28 | 9x9 |

No optimization was done on the grating for the smaller mesas: the depth and size of the grating dots are the same for all pixels.

Each of these different sized pixels was electro-optically characterized. The dark current scaled as expected nicely with the pixel size, confirming that QWIPs don't suffer from any side wall leakage currents. The optical response was measured at 65 K and with 1.5 V detector bias. Fig. 1 shows the results of the measured integrated response as function of the pixel pitch, compared to the simulations.

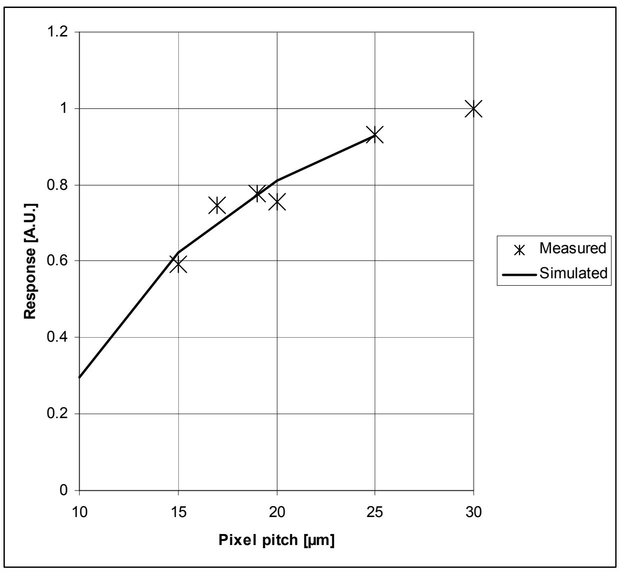



Fig. 1 Response as function of pixel pitch, simulated and measured

As expected we observe a reduction of the responsivity of 40 % for smaller pixels. This is in good agreement with numbers published [5]. Only a discrete number of grating dots fits on a mesa, this means that the grating has to be tweaked for each individual mesa size: the size of the grating dot and the pitch need to be adjusted.

The next logical step after this experiment is the development of a mega pixel QWIP detector with 19 µm pixel pitch. This work has been started, with the following target specification:

Table 2 Target specification mega pixel PFA

| Parameter | Value | Comment |
|---|---|---|
| Array format | 1280 × 720 | |
| Pixel pitch | 19 µm | |
| Temporal NETD mean | < 35 mK | F/2.7 cold shield, 70 K operating temperature, 8 ms integration time, 60 Hz frame rate, highest object temperature 80°C |
| Spatial NETD mean | < 15 mK | |
| Fill factor | > 90 % | (The area ratio of mesa mask layer as drawn to pixel size) |

Some of the remaining issues for such FPA lay in the manufacturing process: the GaAs detector chip is bigger than the maximum reticle size of the lithography equipment, thus stitching will be required. Furthermore the hybridization process needs to be refined, both to be able to handle many pixels as well as the smaller pixel size. These issues, together with the design of a new readout circuit, will be addressed during the coming year.

## 3 NEW IRNOVA FPA

Here we present the performance of the recently at IRnova developed 320 by 256 pixels QWIP focal plane array based on the standard ISC9705 readout. All detectors produced at IRnova are tested at their nominal detector operating temperature, in this case 68 K. The test results of a typical FPA are shown in Table 3 and the conditions in

Table 4.

Table 3 IRnova 320 ER test results

| Parameter | Measurement | Test conditions |
|---|---|---|
| NETD | 21.67 mK | @ 30 °C,<br>Uncorrected for aperture shading effects |
| Spatial Noise | 6.9 mK | @ 42 °C<br>Mapping temperatures 30 and 55 °C |
| Dead pixels | 3 | Deviating response, deviating NETD, deviating Spatial noise |

Table 4 Test conditions

| | |
|---|---|
| Aperture | F/2.6 |
| Detector temperature | 68 K |
| Max scene temperature | 80 °C |

Although the format of this FPA is not the most demanding, we see clearly the strengths of QWIPs: good NETD, but above all very good operability and uniformity. The latter is confirmed when looking at the histogram of the NETD, Fig. 2. The standard deviation of the NETD is 2.6 mK, this is without correction for aperture shading effects.

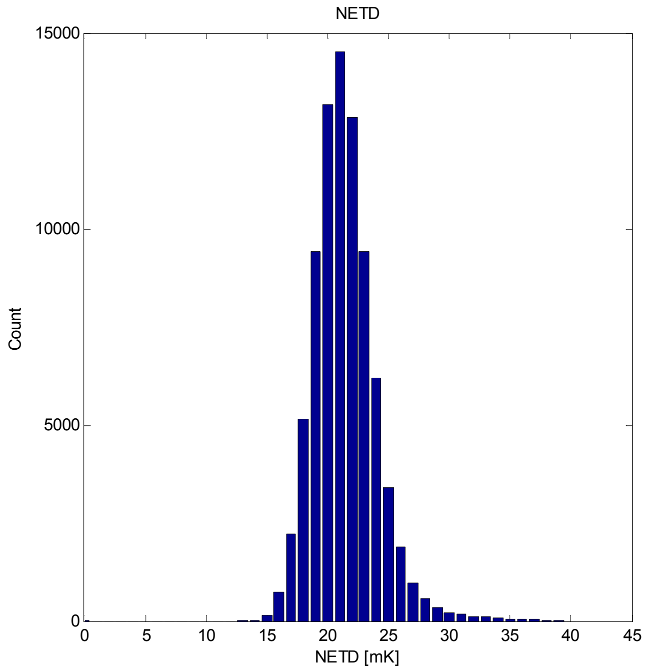



Fig. 2 NETD distribution of a typical 320 by 256 QWIP FPA.

## 4 ESA PROJECT

IRnova participated in the development of QWIPs for space applications within several projects granted by ESA. Requirements imposed on the response, dark current and operation temperature were extremely demanding. To meet them special efforts were taken to improve the quality of the epi-material used for manufacturing of QWIP detectors at IRnova. Special care was also taken to fine-tune the quantum well structure.

The performance of the QWIP structure crucially depends on the quality of the epi materials. Impurities and unwanted incorporations can result in higher dark current, for instance, via impurity-assisted tunneling through the bulk barriers. The first stage of the development of the detectors for space applications revealed that these effects cannot be neglected to achieve the required level of the dark current.

The goal of next development stage was to optimize the growth parameters with respect to Si and C incorporation in the AlGaAs barriers. Various combinations of the V/III source material ratio, growth temperatures and growth rates were used to grow AlxGa1-xAs with two different compositions: x=0.17 and x=0.30. The former composition is relevant to the VLWIR (very long wave infrared) QWIP structures, while the latter is common in QWIPs for the 8-12 µm window. Two types of wafers were grown, one on an exactly oriented (100) substrate, the other on a substrate with a 3° off-cut.

Secondary-ion mass spectroscopy (SIMS) was used to record the atomic concentration profiles through the epi-layers. The analyzed elements were Al (used for layer tracking only), O, Si, and C.

The analysis showed that the growth rates and input V/III gas ratios have no noticeable effect on the Si and C incorporation in $Al_{0.17}Ga_{0.83}As$, whereas a lower growth temperature (650 °C in our case) clearly gives less Si-incorporation, see Fig. 3. The dependence on the growth temperature for C is reversed, but the slightly higher level of C-incorporation at 650 °C can be suppressed by growth on 3°off-cut substrate, see Fig. 4.

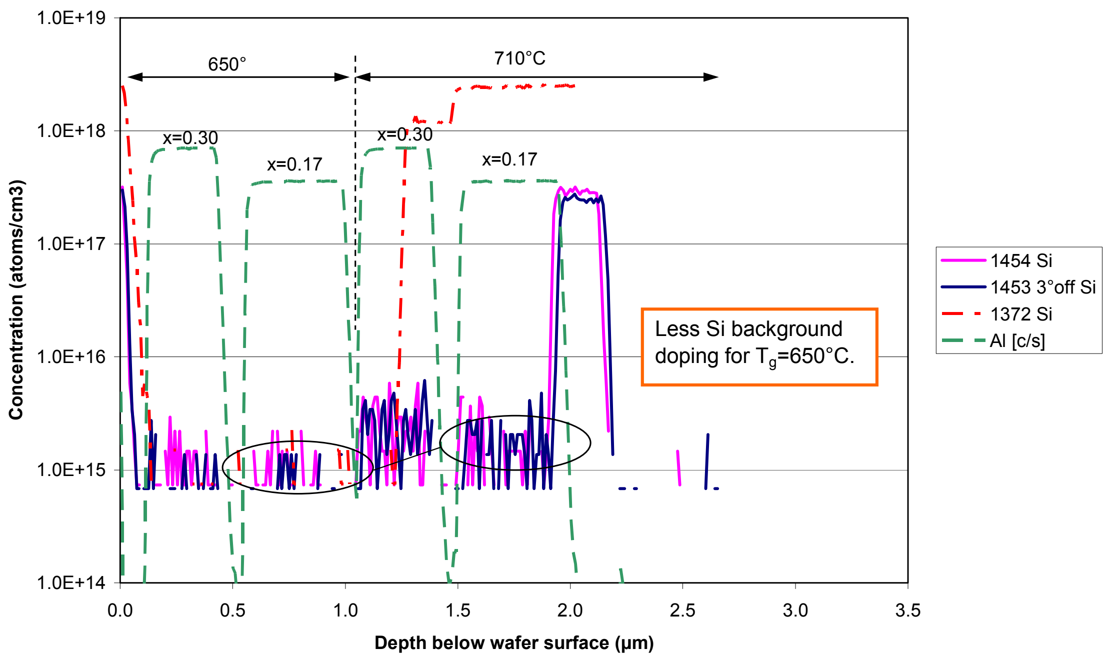



Fig. 3. SIMS profile for Si in AlGaAs barrier material. The detection limit for Si with this technique is approximately $1\times10^{15}$ atoms/cm3.

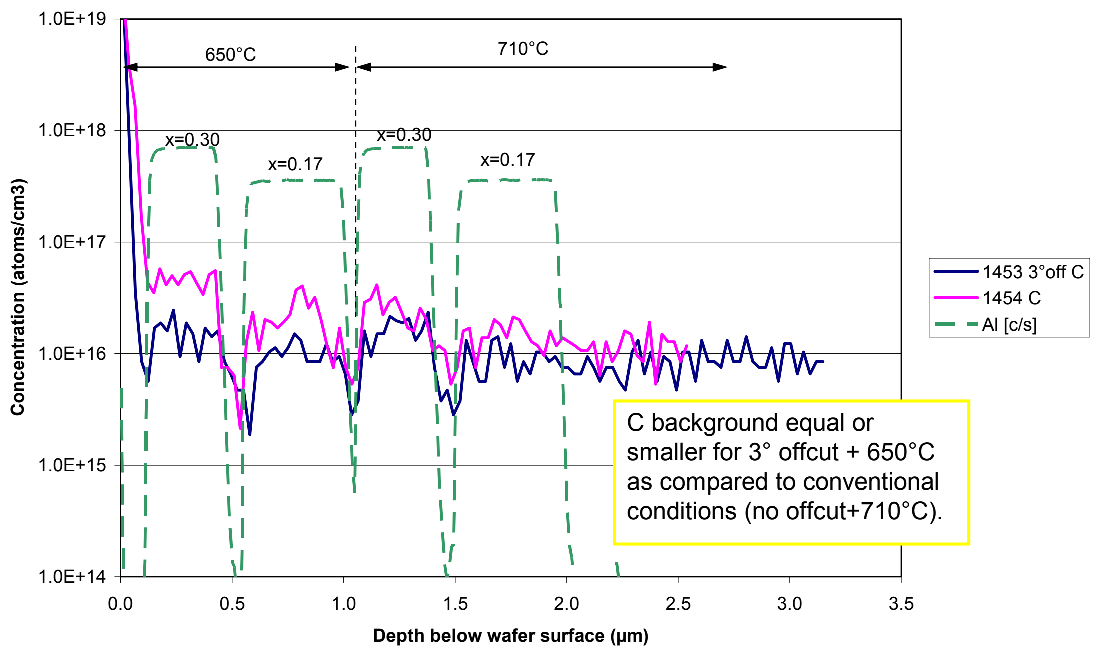



Fig. 4. SIMS profile for C in AlGaAs barrier material.

The conclusion from this experiment is that by growing the QWIP at reduced temperature, perhaps in combination with an offcut substrate, one can reduce the Si impurity background in the barrier material, while maintaining a low C concentration. The other growth parameters need not be changed, except perhaps for necessary fine tuning of the layer growth times in order to keep the structure geometry intact. This is especially important for the applications where the level of dark current is more important than the operating temperature since the purity of the material affects mostly the temperature-independent component of the dark current. The described improvements suggest that the level of the dark current originally specified for instance for the Darwin mission can be achieved at 14-15 K, which was not possible before.

# 5 NEXT GENERATION PHOTON DETECTORS

IRnova and its predecessor and current holding company Acreo have several years' worth of experience of high performance IR (infrared) imaging, taking the QWIP (quantum well infrared photodetector) from basic research to production. But the development does not end there, in a not so distant future new technology requirements need to be fulfilled, namely higher operating temperature and better quantum efficiency whilst maintaining the good uniformity and produceability of QWIP. For that purpose the institute center of excellence IMAGIC has started the project "Technologies for next generation's LWIR FPA". IMAGIC is an institute center of excellence led by Acreo, with the mission to realize next generation electronic imaging devices for non-visible wavelengths from X-ray to thermal IR.

The approach of the ongoing project "Technologies for next generation's LWIR FPA" is to use antimony based superlattices, divided into two tracks. The development track concerns quantum well superlattices based on GaSb and work on structure design, optimization of pixel formation and overgrowth with a passivating barrier layer is performed. The research track works on Quantum Dot (QDs) superlattices. The dots are epitaxially grown by MOVPE (Metal Organic Vapor Phase Epitaxy) and are buried in a barrier material which will reduce the leakage current. The growth is done on GaAs substrates, which will make the future production costs lower.

The project aims for focal plane demonstrators by 2009.

## 5.1 Coupled Dot Infrared Photodetector

Coupled dot infrared photodetectors (CDIPs) correspond to an entirely new approach to realize high performance, cost-effective detector arrays for the LWIR wavelength range with potential major advantages in high sensitivity and low dark current. The basic idea relies on the creation of a narrow effective bandgap due to spatially indirect interband transitions between coupled InAs and GaSb self-organized Quantum Dots with a type-II band alignment arranged in a superlattice (SL) structure on GaAs. The QD arrangement in this photovoltaic detector type is shown in Fig. 5.

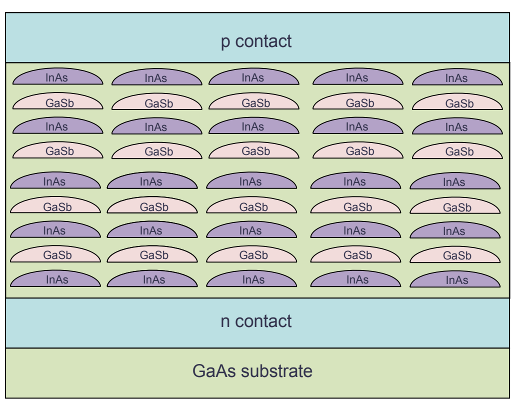



Fig. 5 Schematic dot arrangement showing part of a QD-SL.

Multilayer QD self-assembly results in an array of QD stacks due to strain field distortion around underlying QDs. A thin layer of GaAs is inserted between the QDs to restore the strain situation. The corresponding bulk band structure is shown in Fig. 6. Quantum confinement and strain creates hole-states and electron-states that are localized in the GaSb and InAs dots respectively. The wave functions overlap allowing mini-bands (marked with dashed lines in Fig. 6) to be formed. Transitions between these bands are indirect in real space but direct in k-space.

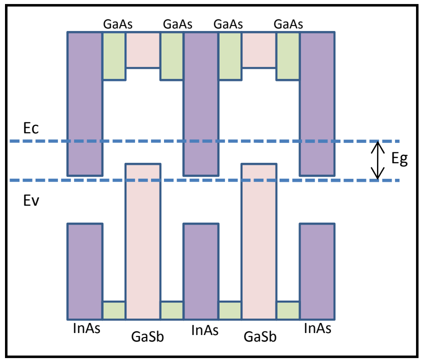



Fig. 6.Bulk band structure in the growth direction.

Numerical simulations of the QD based superlattices electronic structure and absorption properties using the 8x8 k.p method together with strain and confinement models show that it is possible to achieve detection in the LWIR band using the CDIP concept. Different design variations were studied for a detection wavelength of 10 µm. This includes heterojunction QDs (so-called heterodots) where the GaSb dots are grown directly on top of the InAs dots. The estimated absorption coefficients are in the range 1-7×10$^{4}$ cm$^{-1}$, with the assumption of a QD density of 1×10$^{11}$ cm$^{-2}$ as can be seen in Fig. 7.

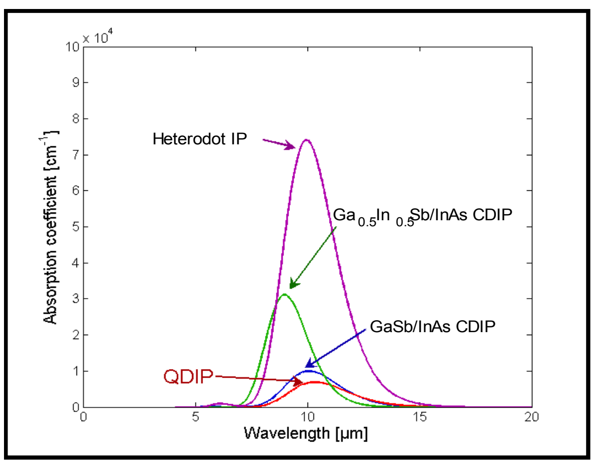
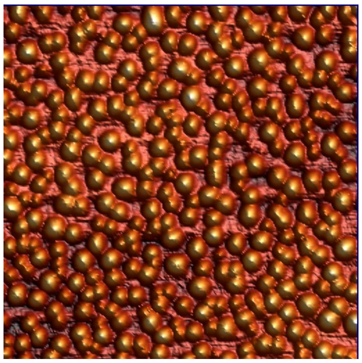



Fig. 7. Simulated absorption coefficients for different CDIP design variations. The value for a dot-in-a-well QDIP developed at Acreo is given as reference. The highest absorption coefficient is achieved for the heterodot-based structure.

In contrast to type-II strained layer superlattice (T2SL) detectors which have been extensively investigated during the past years, these structures will be inherently less sensitive to surface leakage in pixel-sized devices due to the embedding of the QDs in the large-bandgap GaAs matrix material. Furthermore, as opposed to the T2SLs, these structures are grown on standard GaAs wafers which can be obtained at large sizes and low defect densities. The large absorption coefficient together with the broad detection interval potentially gives them an edge over QWIPs.

The growth of InAs and GaSb QDs on GaAs with MOVPE has been demonstrated (Fig. 8) with results in line with the literature [6]-[7]. Heterodots have been grown and the transitions have been identified as type-II lying in the near infrared regime. This blue shift as compared to the design wavelength of 8 µm is believed to be due to Sb segregation and/or Sb-As intermixing phenomena leading to a high As content in the dots. This is a common problem during growth of GaSb/GaAs QDs as well as for T2SL structures [8]-[13]. For a successful realization of CDIPs it is thus of importance to suppress such phenomena, e.g.: using carefully tuned growth conditions and/or gas-switching/purging sequences.



1x1 µm

1x1 µm

Fig. 8 GaSb quantum dots grown on GaAs. Density $4*10^{10}/cm^2$. 5b, InAs quantum dots grown on GaAs. Density $3*10^{10}/cm^2$. The pictures areas are 1x1 µm.

### 5.2 Antimony based type 2 superlattices for LWIR

Infrared detectors based on type II InAs/GaSb superlattices have the potential to reach higher operating temperatures and better responsivity than current QWIPs [14]-[18]. There are known challenges with high leakage currents, specifically currents on the surface of the mesas. In [19] successful passivating regrowth with AlGaAsSb by MBE is shown. In this work we choose MOVPE as the method to do the passivating regrowth.

Detector structures were designed and grown by MBE on p-type doped GaSb substrates. The device structure consists of 190 periods of 11ML InAs/ 5ML GaIn(0.25)Sb of witch the first 90 periods are p-type, followed by 40 periods of unintentionally doped absorber and on top a 60 periods n-type doped contact layer. The material was processed into single diodes with standard semiconductor techniques, but without any special sidewall passivation. After processing, devices were wire bonded to a carrier for characterization.

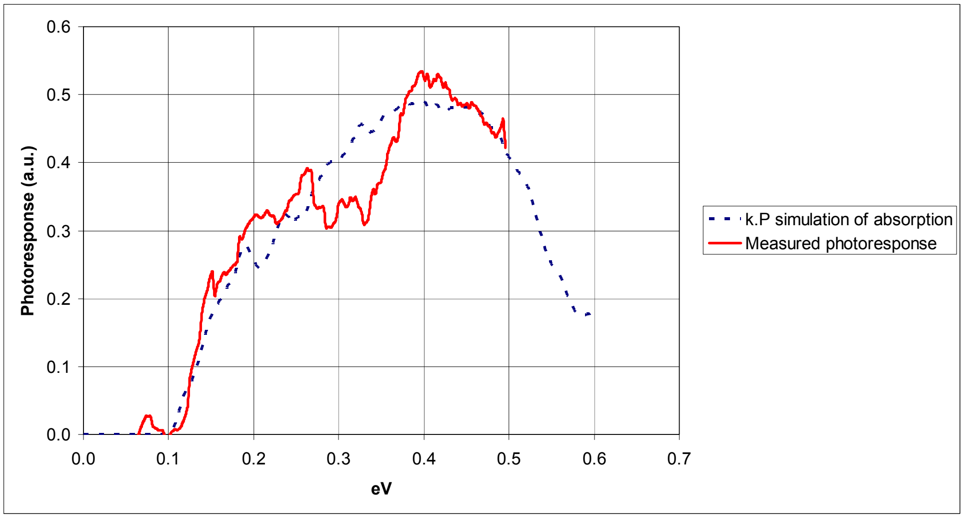



Fig. 9 Simulated and measured Photon response, 0.1 eV corresponds to ~12 µm cut-off.

The results of the optical characterization can be seen in Fig. 9. As can be seen, the measured 100 % cutoff at approximately 0.1 eV (corresponding to 12 µm) is in very good agreement with the modeling. The numerical simulation model of the structure is based on the 8x8 k.p method taking strain into account.

In parallel with simulation and design of the supperlattice structure, a wafer process for the pixilation of the detector material (for example 30 µm pixel pitch) is also established. Experiments with passivating regrowth with AlGaSb with MOVPE show very promising results see Fig. 10. The SEM images show very good side wall coverage. Experiments to determine the passivating properties of this method are currently being carried out.

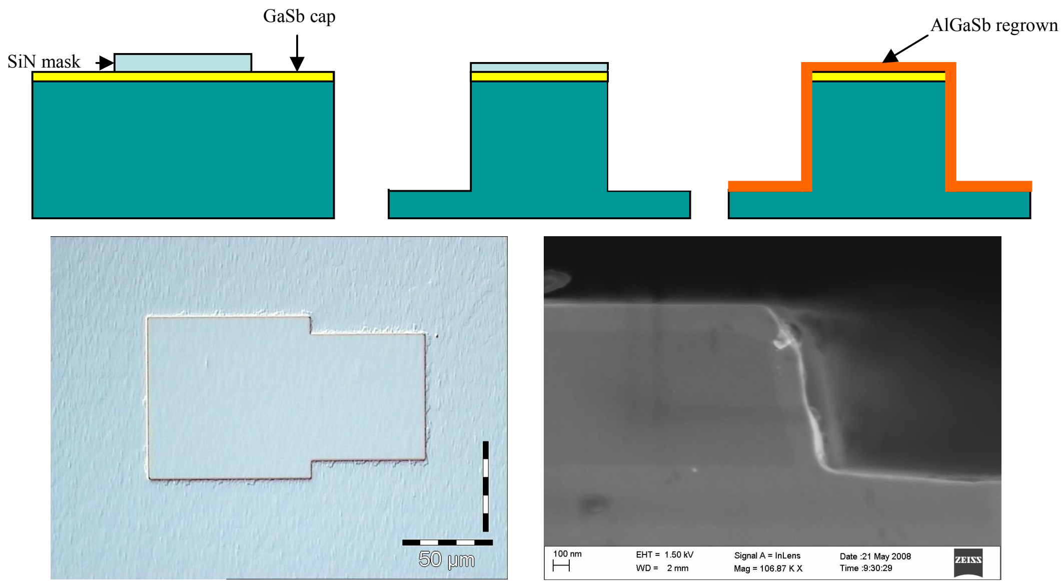



Fig. 10 Regrowth of 150 nm AlGaSb on a dry etched pixel. The upper pictures show the process flow. The pictures below show the processed material, to the left an optical microscope picture from above and to the right a profile picture taken by SEM (Scanning Electron Microscopy).

### 5.3 Antimony based type 2 superlattices for MWIR

In the mid wave infrared the results are very encouraging. Pin detector structures were grown by MBE on p-type doped GaSb substrates. The device structure consists of 190 periods of 9ML InAs/ 10ML GaSb of witch the first 90 periods are p-type, followed by 40 periods of unintentionally doped absorber and on top a 60 periods n-type doped contact layer. The material was processed into single diodes with standard semiconductor techniques. After processing, devices were wire bonded to a carrier for characterization. The electro-optical characterization results are shown in Fig. 11.

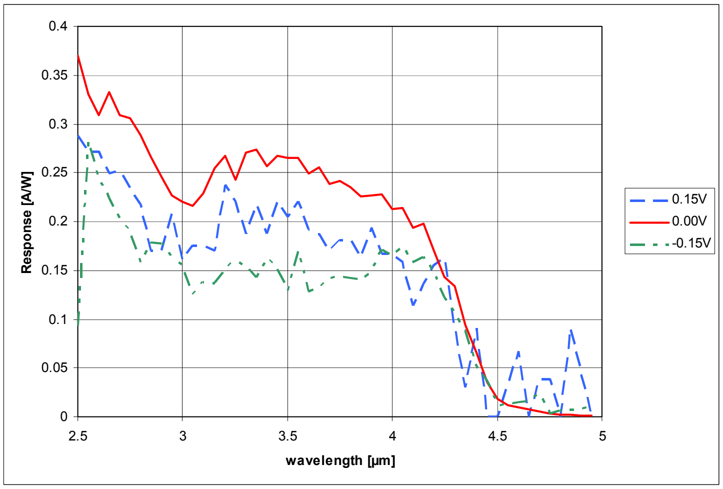



Fig. 11. Experimental results for the MWIR SbSL test structure evaluation.

A response of 0.25 A/W corresponds to ~10 % quantum efficiency. This relatively low QE can be explained by the rather thin absorber layer (~200 nm). Better QEs have been reported with thicker absorber layers.

## 6 CONCLUSIONS

QWIPs are very well suited for big focal plane arrays with high uniformity and operability. There is on a lot of fronts still room for improvements, for instance the shape and size of the mesa and grating can be optimized for even better lightcoupling. Furthermore, the growth conditions of the detector material by means of MOVPE can still be improved.

Work on the next generation high performance LWIR photodetector is carried out to fulfill the technology requirements of the future. Superlattices are the choice of detector type because they give high performance in combination with good manufacturability. Coupled quantum dots might be the answer, but there are still significant technological hurdles to overcome. The results of the T2SLs are promising when it comes to array processing, overgrowth of barrier material and quantum dot growth. However, surface passivation and quantum dot absorption wavelength is still in need of improvements.

The project goal is to have a quantum well superlattice FPA demonstrator in June 2009 and to have a quantum dot superlattice demonstrator by December 2009.

## 7 ACKNOWLEDGEMENTS

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