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Type II superlattice technology for LWIR detectors


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ABSTRACT

SCD has developed a range of advanced infrared detectors based on III-V semiconductor heterostructures grown on GaSb. The XBn/XBp family of barrier detectors enables diffusion limited dark currents, comparable with MCT Rule-07, and high quantum efficiencies. This work describes some of the technical challenges that were overcome, and the ultimate performance that was finally achieved, for SCD’s new 15 μm pitch “Pelican-D LW” type II superlattice (T2SL) XBp array detector. This detector is the first of SCD’s line of high performance two dimensional arrays working in the LWIR spectral range, and was designed with a ~9.3 micron cut-off wavelength and a format of 640 × 512 pixels. It contains InAs/GaSb and InAs/AlSb T2SLs, engineered using k · p modeling of the energy bands and photo-response. The wafers are grown by molecular beam epitaxy and are fabricated into Focal Plane Array (FPA) detectors using standard FPA processes, including wet and dry etching, indium bump hybridization, under-fill, and back-side polishing. The FPA has a quantum efficiency of nearly 50%, and operates at 77 K and F/2.7 with background limited performance. The pixel operability of the FPA is above 99% and it exhibits a stable residual non uniformity (RNU) of better than 0.04% of the dynamic range. The FPA uses a new digital read-out integrated circuit (ROIC), and the complete detector closely follows the interfaces of SCD’s MWIR Pelican-D detector. The Pelican-D LW detector is now in the final stages of qualification and transfer to production, with first prototypes already integrated into new electro-optical systems.

Keywords: Infrared Detector, Focal Plane Array, Type II superlattice, XBn, XBp, ρBp, LWIR.

1. INTRODUCTION

In a pioneering article† entitled “a new semiconductor superlattice” published in 1977, Sai-Halasz, Tsu and Esaki proposed that a superlattice based on alternating layers of InAs and GaSb would exhibit rather unique properties, including a zero bandgap at a critical value of the layer thicknesses. In this respect, the new superlattice bore a close relationship with the alloy, HgCd1-xTe, where the bandgap vanishes at a critical value of the composition parameter, x (See Figure 1). HgCd1-xTe has become one of the most widely used tunable infrared detector materials, because it is a versatile technology that can match the characteristic photon wavelength of most infrared applications. On the other hand, InAs/GaSb superlattices, also known as type II superlattices (T2SLs), have only recently been considered to be a
viable alternative technology to InAs/GaSb, due to the more challenging crystal growth that is required. T2SLs must be grown by molecular beam epitaxy (MBE), which has taken longer to mature to a reliable commercial production tool than the liquid phase epitaxy technique that is used most widely in the production of InAs/GaSb. An important factor driving T2SL development, however, is that commercial 3” or 4” GaSb substrates can be used for their growth, while smaller and more expensive CdZnTe substrates must be used for the highest quality InAs/GaSb.

Yet two more technological hurdles still had to be overcome, before T2SL technology began to look truly competitive. The first was the suppression of generation-recombination (G-R) limited dark current, which is absent in high quality InAs/GaSb photodiodes, and the second was device passivation. A novel barrier device, known as an XB$p$ detector, was developed at SCD, which contains two types of T2SL: InAs/GaSb for the photon absorbing layer (AL) and the contact layer (CL), and InAs/AlSb for the barrier layer (BL). As shown in the “$pB_p$” version of this device in Figure 2, the AL and BL T2SLs are doped $p$-type which ensures that there is no depletion layer in the narrow bandgap AL. The figure shows how G-R current is generated in the depleted BL through mid-gap Shockley-Read-Hall (SRH) traps with an activation energy close to half of its bandgap. Since this bandgap is more than twice that of the AL, the G-R current is negligible compared to the diffusion current coming out of the AL. For this current, the activation energy is equal to the full AL bandgap, since all SRH traps are occupied. In this work it will be shown that the dark current in a T2SL XB$p$ device is quite close to the Rule 07 value, which is the state of the art metric for InAs/GaSb photodiodes.

The second technological hurdle that had to be overcome was a reliable passivation treatment of the processed XB$p$ devices, which is compatible with all of the standard FPA processes, including wet and dry etching, indium bump hybridization, glue under-fill, and back-side polishing. The development of this passivation at SCD is the final step in a fabrication process that has enabled the fabrication of long wave infrared (LWIR) T2SL FPAs with a performance comparable to high quality Hg$_{1-x}$Cd$_x$Te FPAs. The design and performance of these FPAs is the subject of this paper.

In section 2, the design and performance of T2SL barrier devices is discussed, with particular emphasis on device simulation and surface passivation. The next section introduces the key

**Figure 1**
The zero bandgap state occurs when the bands with s- and p-like orbital symmetry cross at a critical value of (a) the composition parameter, $x$, in Hg$_{1-x}$Cd$_x$Te and (b) the InAs and GaSb layer thicknesses in a type II superlattice.

**Figure 2**
The profiles of the conduction and valence band edges in a T2SL $pB_p$ device. The AL (left) and CL (right) are made from an InAs/GaSb T2SL and the BL, from an InAs/AlSb T2SL. The broken wavy arrows represent thermal generation processes in the AL and BL, and the asterisk, a mid-gap SRH trap.
parameters of SCD’s new 15 μm pitch, 640 × 512 read-out integrated circuit (ROIC) designed to operate with XBp devices (equivalent polarity to n-on-p photo-diodes). The radiometric characteristics of the new FPA are presented in section 4, using data from over 200 FPAs from our new Pelican-D LW production line. The conclusions are summarized in section 5.

2. DESIGN AND PERFORMANCE OF T2SL BARRIER DEVICES

The T2SL structures used in this work were grown in-house in a Veeco GenIII MBE system, on 3 inch “epi-ready” GaSb(100) substrates. The InAs/GaSb (AL and CL) and the InAs/AlSb (BL) superlattices had “InSb-like” interfaces in order to achieve a good lattice match with the substrate. Further growth details may be found in Ref. 7. The good reproducibility of the MBE growths enabled optimizations of both the device structure and the wafer process, which are further elucidated below.

In order to achieve a smooth conduction band profile but a large barrier in the valence band as depicted in Figure 2, a method of band structure and optical field simulation was developed at SCD, based on the k · p theory and optical transfer matrix (OTM) techniques. The band structure simulation introduces a number of novel features including the use of an interface matrix, and a way of calculating the Luttinger parameters from standard reference values.8,9 Figure 3(a) shows a plot of the bandgap energy as measured from the position of the photoluminescence (PL) peak at 10K vs. the calculated bandgap for more than 30 T2SL samples. The calculated value was based on InAs and GaSb layer widths

![InAs/GaSb](image1)

![InAs/AlSb](image2)

Figure 3
Comparison between calculated band gaps and PL peak energies measured at 10K for (a) more than 30 InAs/GaSb T2SLs spanning the MWIR to LWIR wavelength range, and (b) 14 InAs/AlSb T2SLs. The thin lines show deviation by ±kBT at 77 K from ideal behavior (thick line).

![Log Jdark vs. 1000/T](image3)

Figure 4
Log Jdark vs. 1000/T in pBp, p barrier device (bias = 0.6V) and n-p diode (bias = 0.1V), each with an InAs/GaSb active layer bandgap wavelength of λc≈10 μm (mesa area = 100×100 μm²)
determined to an accuracy of ±0.2 monolayer (ML) from X-ray diffraction and MBE beam flux measurements, as described in Ref. 8. It can be seen in Figure 3(a) that the measured and calculated energies match the ideal behavior (thick line) to within an accuracy of ±k_BT at 77 K (thin lines), for bandgap energies which span the full range from LWIR to MWIR. Figure 3(b) shows equivalent results for 14 InAs/AlSb superlattices. In this case, error bars are shown for those samples where the layer width accuracy was less than ±0.2 ML.

The advantage of the barrier device architecture over that of a simple diode is demonstrated in Figure 4. This figure compares a standard LWIR n-on-p diode based solely on an InAs/GaSb T2SL and operating at a bias of 0.1V, with a LWIR pB_xp device based on the design in Figure 2, and operating at a bias of 0.6V. Both devices have an active layer band gap wavelength close to 10 μm. The barrier device (blue line) is diffusion limited down to 77 K, while the diode (red line) is G-R limited at this temperature, with a dark current over 2 order of magnitude larger. The dark current in the barrier device of Figure 4 and in all of our XBp test devices is only about one order of magnitude greater than the Hg0.5Cd0.5Te Rule-07 value. This is discussed further below, where the results on test devices are compared directly with measurements made on FPAs. Although higher than the Hg0.5Cd0.5Te value, it is shown that the dark current is in a range that allows good and stable background limited performance (BLIP) at 77 K.

In order to understand the role of surface passivation in our barrier devices, we have performed a series of experiments on pB_xp gate controlled device (GCD) structures, with mesas etched into the BL. Figure 5(a) shows the design of such a GCD, which was used to monitor changes in the barrier surface potential caused by the glue under-fill process. A small array of standard devices and GCDs was bonded to a silicon fan-out circuit with indium bumps, and the electrical characteristics of the devices were measured as a function of temperature, before and after injection of a glue under-fill, and polishing of the GaSb substrate down to a final thickness of about 10 μm. Substrate thinning is required in order to relieve stress on cooling. It was found that after performing the under-fill process, all of the standard devices without gates showed very large leakage currents. These currents were several orders of magnitude greater than the true device dark current that could be measured before under-fill. The results were similar for a number of different glues that were tested. In contrast, the true dark current could be restored in the GCDs, by applying a suitable negative bias to the gate. Figure 5(b) shows the device dark current at 77 K and a constant operating bias (V_{CL} = 0.8V) as a function of the gate bias. Before under-fill, a plateau of minimum dark current can be seen which corresponds to the true device current. Over the range of the plateau (−4V ≤ gate bias ≤ 0V) the I-V_{CL} characteristic of the device shows true diffusion limited behavior, where the dark current near V_{CL} = 0.8V is virtually bias independent and has an activation energy close to the bandgap of the AL. Outside this range, the dark current rises steeply,
indicating an additional leakage path. After the under-fill and polishing process, the plateau of minimum dark current maintains the same value as before, but is shifted to negative gate bias by approximately -12V. This shows that at zero gate bias, and in devices with no gate, the under-fill induces strong surface accumulation on the BL. This layer of negative charge opens a leakage channel between devices (as depicted in Figure 5(a)) and can short all of the devices to common through a single low resistance defect that shunts the BL. Only by applying a gate bias of between about -12 and -16V is the negative surface accumulation layer suppressed.

In a real FPA detector, it is not feasible to use a negatively biased gate electrode around each device without introducing an extra contact per pixel and sacrificing device yield and fill factor. Instead, once the cause of the dark current leakage had been identified, we were able to develop a suitable passivation process that suppresses the surface accumulation even after under-fill and polishing.

3. 640 × 512/15 μm DIGITAL ROIC

The new ROIC has an architecture that closely follows that of the mature and successful MWIR Pelican D ROIC11. This approach was chosen due to the excellent performance expected in terms of readout noise, Residual Non Uniformity (RNU), power dissipation and frame rate. Another important incentive was to support our incumbent customers with fast integration into systems and cameras. Nevertheless, the new T2SL LWIR technology poses two important challenges for the ROIC design:

1. The device polarity requires a polarity inversion in the ROIC circuitry.
2. The higher photon flux compared with the MWIR imposes very short integration periods due to the limited area available for the integration capacitors.

To overcome this problem we have implemented a high frame rate (up to 360Hz) with frame averaging (up to 8 frames) performed in the proximity electronics. This enables us to achieve an NETD value @ F/2.7 and 30Hz of less than 15mK.

The ROIC was tested at room temperature and 77 K and the results compared favorably with preliminary predictions. Table 1 presents the measured performance.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
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<td>Well Capacity</td>
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</tr>
<tr>
<td>Noise Floor</td>
<td>&lt; 1300e(^{-2})</td>
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<tr>
<td>ROIC RNU</td>
<td>&lt; 0.025% of DR</td>
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<tr>
<td>Dynamic Range</td>
<td>5350</td>
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<tr>
<td>ADC Resolution</td>
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<tr>
<td>Maximum Frame Rate</td>
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<td>Integration modes</td>
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</tbody>
</table>

Table 1
Pelican-D LW ROIC performance at 77 K

4. PELICAN-D LW FPA

"Pelican-D LW" is the first in our new line of LWIR XBP FPAs manufactured at SCD. The detector operates at 77 K and is based on a 15 μm pitch, 640 × 512 FPA bonded to the new digital silicon ROIC, described above. The FPA has a nominal T2SL cut-off of 9.5 μm, but in the final Integrated-Detector-Cooler assembly (IDCA) we normally include a cold filter with a cut-off wavelength of 9.3 μm. More than 80 FPAs have been made with this nominal wavelength, but in order to demonstrate the technology in more general terms, results are shown for a larger number of FPAs spanning a useful T2SL cut-off wavelength range between 8.7 and 10.3 μm. Unless an IDCA is stated explicitly, measurements were performed in a laboratory test Dewar without a cut-off filter.

Figure 6(a) shows the FPA dark current distribution at 77 K for 5 FPAs with cut-off wavelengths spanning the nominal value of 9.5 μm. The median dark current value for a cut-off of 9.4 μm is close to 100 pA and the distribution is quite narrow with a full width at half maximum of only ~6% of the median (red curve in Figure 6(a)). The maximum distribution width in Figure 6(a) is 12%, for the two FPAs with a 9.8μm cut-off, which is still quite narrow. Note that these two FPAs have virtually identical distributions, showing the high reproducibility of our FPA process. None of the distribution curves have a significant high current tail, and their narrow widths demonstrate a high degree of uniformity. A narrow dark current distribution is desirable for the stability of the FPA against temperature or bias fluctuations.
The median dark current values of all five FPAs are about one order of magnitude higher than the dark current range predicted by $\text{Hg}_x\text{Cd}_{1-x}\text{Te}$ Rule-07. Results for these and more FPAs are shown on a Rule-07 plot in Figure 6(b), together with similar results from test devices spanning a similar wavelength range. In each case, the cut-off wavelength (in $\mu$m) is given in the legend, as measured by photoluminescence spectroscopy at 10K, and for the FPAs, the number of FPAs measured is also stated. The standard deviation of the FPA dark current is plotted as positive and negative error bars, and is generally quite small. It can be seen that the distributions of FPA and test device results fall in the same range which is slightly more than one order of magnitude above the solid blue Rule-07 line.

![Image of Figure 6](image_url)

**Figure 6**
77 K dark current: (a) normalized distribution of five Pelican-D LW FPAs with cut-off wavelengths between 9.1$\mu$m and 10.3$\mu$m (b) comparison of test devices and FPAs with MCT Rule 07 (solid blue line) over a similar range of cut-off wavelengths

The quantum efficiency at 77 K: (a) for a 1 pass detector with AL = 4.5 $\mu$m as a function of wavelength, comparing measured spectrum (blue) and simulation based on $k\cdot p$ theory (purple) (b) simulated as a function of AL thickness for both one pass (solid line) and two pass (broken line) detectors. Measured values, calculated by averaging over the 300 K black body spectrum from 8.0 $\mu$m (filter cut-on value) to detector cut-off wavelength, are shown as points for the average of 144 FPAs with a 4.5 $\mu$m AL and 25 FPAs with a 3 $\mu$m AL. The error bars show the standard deviation of the FPA results.
The standard deviation of water with A, operating at 7°C.

The magenta line in Figure 7 (a) compares the spectral response of a Pelican-D LW FPA measured at 77 K with the simulated spectrum based on the $k \cdot p$ and OTM calculation, described above. The measurement was performed using a Bruker Equinox FTIR spectrometer and is quite noisy due to a weak globar source and to some atmospheric absorption along the measurement path. Nevertheless, it can be seen that very good agreement is obtained with the simulation, for a T2SL with a cut-off wavelength of 9.46 μm. The fitted inhomogeneous broadening at the band edge was 10 meV, which agrees very well with the fluctuations in the band edge energies calculated from the $k \cdot p$ model due to single monolayer interface steps. The maximum QE in the measured spectrum is 60%. The Pelican-D LW FPA has an AL thickness of 4.5 μm, and the current version is a one pass device. The detector QE, denoted $<\text{QE}>$ in Figure 7 (b) is the value obtained when the spectrum in Figure 7 (a) is averaged over the 300K black body spectrum from 8.0 μm (filter cut-on value) to the detector cut-off wavelength. In this figure, the simulated $<\text{QE}>$ is plotted as a function of the AL thickness for one pass (solid line) and two pass (broken line) detectors, respectively. The one pass values are compared with the average of all the results from the first 144 Pelican-D LW FPAs from our new production line, where the result for a given FPA is the mean of $<\text{QE}>$ over all of its pixels. The standard deviation of the FPA values is shown as positive and negative error bars. Results for 25 similar FPAs with a 3μm thick AL are also shown. In both cases the average value falls very close to the simulated value. The simulations in Figure 7 (b) demonstrate that it should be possible to achieve a $<\text{QE}>$ of about 60% in a two pass version of the Pelican-D LW detector with the same AL thickness of 4.5 μm.

The high uniformity of our T2SL FPA technology is well demonstrated in Figure 8, which shows a map of the raw signal registered (in Digital Levels) when the Pelican-D LW FPA is placed in front of a black body at 35°C before any non-uniformity correction (NUC) has been performed. The map is very uniform, with no stains, large clusters or other variations across its area. This in turn leads to a very low RNU after a two point NUC (2PC) is performed. The magenta line in Figure 9 shows a plot of RNU vs. well fill (WF) for an IDCA with this FPA, measured using different black body temperatures and a constant integration time, with a 2PC correction.

Figure 10
NETD distribution of the Pelican-D LW FPA at 77 K and at a frame rate of 30 Hz.

The high uniformity of our T2SL FPA technology is well demonstrated in Figure 8, which shows a map of the raw signal registered (in Digital Levels) when the Pelican-D LW FPA is placed in front of a black body at 35°C before any non-uniformity correction (NUC) has been performed. The map is very uniform, with no stains, large clusters or other variations across its area. This in turn leads to a very low RNU after a two point NUC (2PC) is performed. The magenta line in Figure 9 shows a plot of RNU vs. well fill (WF) for an IDCA with this FPA, measured using different black body temperatures and a constant integration time, with a 2PC correction.

Figure 11
$<\text{QE}>$ map of the Pelican-D LW FPA operating at 77 K.
The RNU remains below 0.02% of the dynamic range for WF values in the range 40 - 80%. Moreover, the image is very stable for many hours without any further corrections, as shown by the red line, which was registered one hour after the 2PC was performed. The dashed lines show RNU curves after switching the detector off and then immediately back on (black), or back on the next day (blue), and performing a one point offset NUC (1PC). In all cases the RNU curves remain within ~0.01% of the original calibration curve.

At 65% well fill of its 6Me capacitor and a frame rate of 240Hz, Pelican-D LW offers an NETD of 36mK when configured with F/2.7 optics. By averaging 8 frames at a time, the detector operates at an effective frame rate of 30 Hz. The NETD distribution measured under these conditions for the Pelican-D LW FPA is shown in Figure 10. The distribution is narrow and symmetric with no pronounced tailing. The peak value is 13 mK which is a reduction of \(\sqrt{8}\) relative to the single frame value. This is as expected for pure shot noise, and shows that any noise introduced by the averaging procedure is negligible.

In Figure 11 we show a map of the pixel \(<QE>\) measured in front of a black body at 35°C for the same FPA as in Figure 10, in which none of the defective pixels have been removed. The total number of both hard and soft defects on the FPA, defined according to SCD’s stringent production line criteria, is 1446 giving an FPA operability of 99.56% in this case. The \(<QE>\) map in Figure 11 shows an almost constant value of ~ 48% across the whole FPA, which agrees quite well with
the value expected for a one pass detector with the same AL thickness (4.5 µm) discussed above. If we define the BLIP temperature as the detector operating temperature at which the dark current is equal to the photocurrent, the QE and dark current results discussed in this section yield a BLIP temperature of 87 K for a single pass Pelican-D LW FPA with F/2.7 optics. This is significantly higher than the operating temperature of 77 K. At 77 K, the dark current is more than 10x smaller than the photocurrent and as noted above, its distribution is narrow, making for good image stability against small temperature fluctuations.

Figure 12 shows the variation of NETD and operability values for the first 75 Pelican-D LW FPAs coming from our new production line. Only 2 FPAs exhibit an NETD of more than 15 mK, and more than 65% of the FPAs have an operability above 99%.

Finally, in Figure 13, we show an image at 5 km registered with a demonstration camera containing a Pelican-D LW FPA operating at 77 K, and in Table II we show both the appearance of the IDCA itself and a listing of its current performance specification.

5. CONCLUSIONS

In this article we have presented Pelican-D LW, which is SCD’s new LWIR FPA detector. It has a format of 640 × 512 with a 15 µm pitch, and operates at 77 K with a nominal detector cut-off wavelength, defined currently by a cold filter, of 9.3 µm. The pixel operability is above 99%, according to SCD’s standard production line criteria for the definition of bad pixels. The present version is a single pass detector with a QE of ~48% and exhibits very high uniformity and stability of its response and dark current. The FPA has a very stable RNU below 0.02% of the dynamic range (DR) for well fills between 40 and 80%. Over the entire working range of the detector, the RNU is expected to be below 0.04%. The active sensing material is based on a patented diffusion limited XBp barrier architecture, where an InAs/GaSb T2SL is used for the AL and an InAs/AlSb T2SL is used for the barrier layer. A robust passivation process has been developed at SCD that allows glue under-fill and substrate thinning, after bonding the sensor array with indium bumps to the custom designed silicon ROIC. We have demonstrated sophisticated simulation techniques which can predict the detector cut-off wavelength and spectral response a-priori, according to the individual layer thicknesses chosen for each superlattice period, and the overall active layer stack thickness. Pelican-D LW demonstrates the versatility of InAs/GaSb as a tunable active layer detector material. The highly reproducible results from our new LWIR detector production line show that this material can now be considered to be a realistic alternative to HgCd1-xTe for small pitch, high performance LWIR and dual-color FPA detectors.

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REFERENCES