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Manufacturability of type-II InAs/GaSb superlattice detectors for infrared imaging

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Type-II InAs/GaSb superlattice detectors and focal plane arrays (FPAs) with cut-off wavelength at 5.1 μm have been studied. For single pixel devices, dark current densities of 1×10^-6 A/cm^2 and quantum efficiencies of 53% were measured at 120 K. From statistics of manufactured FPAs, an average FPA operability of 99.87% was observed. Furthermore, average temporal and spatial noise equivalent temperature difference (NETD) values of 12 mK and 4 mK, respectively, were deduced. Excellent stability of FPAs after non-uniformity correction was observed with no deterioration of the ratio between spatial and temporal noise during a two hour long measurement. Also after several cooldowns the ratio between spatial and temporal NETD stayed below 0.6.

In recent years InAs/InGaAsSb Type-II superlattices (T2SLs) have proven to be excellent material for high end infrared (IR) detectors and are now competing with the traditional state-of-the-art technologies. Good detector performance has been demonstrated for single pixel detectors as well as for focal plane arrays (FPAs) [1]. Several companies are now manufacturing both mid wave (MW) and long wave (LW) detectors based on T2SLs [2]. One of the major advantages of this
technology is the good manufacturability due to mature III/V-processing. Another advantage is the flexibility to tailor the cut-off wavelength to any desired detection wavelength in the IR wavelength region. In this paper, we will show proof of the good manufacturability of these detectors by presenting statistics from the production of MWIR 320×256 InAs/GaSb FPAs. Statistics show that temporal and spatial noise equivalent temperature difference (NETD) levels of 12 mK and 4 mK are obtained repeatedly. In a study of the image stability of T2SL detectors, no deterioration of the ratio between spatial and temporal noise over time was observed. It was also shown that the non-uniformity correction (NUC) remains stable even after repeated detector temperature cycling. When studied over a large scene temperature, the spatial noise was still less than 60% of the temporal noise.

All MW detector structures studied were epitaxially grown on 3-inch n-type (Te-doped) GaSb (100) substrates using solid source molecular beam epitaxy (MBE). The detector structures are based on a double heterostructure design with a large band gap n-SL contact layer, a lightly doped n-type M-superlattice (M-SL) barrier [3], a weakly doped p-type InAs/GaSb SL absorber with cut-off wavelength of 5.1 µm, a lightly doped p-type SL contact and finally a bulk GaSb layer. Single pixel detectors (170 µm × 170 µm) and FPAs with 320x256 pixels and 30 µm pixel pitch are routinely fabricated from this detector material. Standard III/V processing techniques were used to fabricate the FPAs. The pixels were formed by a combination of dry and wet etching [4] and passivated using a dielectric passivation [5]. Mirror, contact metal and indium bumps were evaporated onto the pixels before dicing. The arrays were then hybridized to ISC9705 read out circuits, underfill was deposited, the GaSb substrate was fully removed and finally an antireflection (AR) coating was applied. All FPA measurements were performed at temperatures in the range 80-85 K, with f/2 optics.
The performance of the T2SL detectors was studied for single pixel devices as well as for FPAs. First, bias and temperature dependencies of the dark current and the quantum efficiency (QE) were studied for single pixel detectors. The temperature dependence study of the QE shows an increase of the QE with increasing temperature (Figure 1a). The peak QE value (measured at the wavelength $\lambda = 3.4 \, \mu m$) increased from 37 % to 51 % as the temperature was increased from 70 to 110 K, while the QE plateaus for temperatures between 110 K and 150 K (Figure 1b). The absorption QE was also measured to enable comparison with the detector QE. At $\lambda$=3.4 $\mu$m, absorption QE values of $\sim$70% were observed (Figure 1c). The difference between the absorption QE and the detector QE indicates that all carriers excited by the incoming radiation are not collected, i.e. the carrier diffusion length is shorter than the absorber thickness. The observed temperature dependence of the detector QE could then be caused by variation of the diffusion length ($L$) with temperature. The diffusion length is given by:

$$L = \sqrt{D \tau} = \sqrt{\frac{kT}{e \mu(T, N_A)\tau(N_A)},} \quad (1)$$

where $D$, $\tau$, $k$, $T$, $e$ and $\mu$ in Eq. (1) correspond to the diffusivity, the minority carrier lifetime, Boltzmann’s constant, temperature, the electron charge and the mobility, respectively. The temperature dependence of the diffusion length is mainly governed by the temperature dependence of the mobility since the minority carrier lifetime is approximately constant in the studied temperature regime [6]. In the low temperature regime, the mobility is assumed to be limited by impurity scattering ($\propto T^{3/2}$) while at higher temperatures it is limited by phonon scattering ($\propto T^{-3/2}$) [7]. The diffusion length is consequently expected to increase proportional to $\sim T^{1.25}$ in the low temperature regime while it will decrease as $\sim T^{-0.25}$ at higher temperatures. The measured temperature dependence of the QE varies similarly to the anticipated temperature trend of the
diffusion length in the low temperature regime (dashed line, Fig 1b), which corroborates the hypothesis that the QE is limited by the diffusion length. In order to further improve the detector QE, the detector design consequently needs to be adjusted to make the diffusion length longer than the absorber thickness at all temperatures of interest.

The dark current density vs. applied bias ($V_b$) was studied for single pixel devices at different operating temperatures (Figure 2a). The dark current density at $V_b = -50$ mV increases from $2 \times 10^{-9}$ A/cm$^2$ at $T = 80$ K to $2 \times 10^{-3}$ A/cm$^2$ at $T = 170$ K. At temperatures ≤ 120 K, all dark current densities fall below $1 \times 10^{-6}$ A/cm$^2$. Flat bias dependence of the dark current density is observed for high temperatures, which is significant for diffusion limited dark current. For lower temperatures, the shapes of the $j(V)$ curves change, which indicate that other dark current components than diffusion current are dominating at those temperatures. An Arrhenius plot of the dark current at $V_b = -50$ mV is shown in Figure 2c. From the Arrhenius plot it is observed that the temperature dependence of the dark current is well approximated by the expression for the diffusion dark current $j_{\text{diff}} \sim T^3 \exp(-E_a/kT)$ in the temperature range $T = 110 – 170$ K. The activation energy ($E_a$) calculated from the data fit in this temperature regime is 236 meV (5.24 µm), which is close to the band gap of 245 meV estimated from the absorption curve measured at 77 K on the same material (Figure 1c). At temperatures below 110 K the activation energy decreases. Fitting of the different dark current components (diffusion, generation-recombination (G-R) and trap assisted tunneling (TAT)) to the measured dark current density at 110 K, corroborate that diffusion dark current still is the dominating dark current source at 110 K for low applied biases (as was observed in the Arrhenius plot). The G-R and TAT currents do however give significant contributions to the dark current at 110 K. As the temperature is further decreased, the tunneling dark current starts to dominate as this component is temperature independent.
Four different measures were used to study the reproducibility and stability of the FPAs fabricated from these detector structures. The first two measures are the temporal and spatial noise. The temporal noise is a measure of the variation of the signal with time, while the spatial noise is a measure of how much pixels deviate statistically from their neighbors when illuminated by a uniform and stable black body source. The temporal noise of each pixel in time was obtained from a series of raw images taken in front of a 30 °C black body source, f/2 optics, integration time 8 ms and a well fill of about 50%. The temporal NETD was calculated by dividing the median temporal noise of all pixels in the FPA with the response per Kelvin. Statistics from the fabricated FPAs (Figure 3a) shows that the average temporal NETD is on the order of 12 mK, very close to the theoretical limit for a background limited detector. The temporal noise distributions observed for these FPAs are very narrow with no tail as demonstrated in Figure 3b. To calculate the spatial NETD, the median value in time of each pixel is calculated to generate a single image (minimizing the effect of temporal noise). This image is then divided into blocks of 5×5 pixels, and the standard deviation of all pixel values in each block is calculated. The spatial NETD is the median of all these standard deviation values divided by the response per Kelvin. Statistics from the fabricated FPAs (Figure 3a) shows that the average spatial NETD is approximately 4 mK. In order to get good image quality, the spatial NETD should be lower than the temporal NETD, which is well fulfilled in this case.

The third measure used to study the stability of the FPAs is the variation of the temporal and spatial NETD, both with temperature cycling and within a single cool-down. The integration time was set to 1 ms in order to cover a wider temperature range and get access to a high instantaneous signal dynamics. In the two-point NUC, the spatial noise was cancelled out at two temperatures (25 °C and 70 °C) using two different black body sources (see Figure 4a). 100% correctability is
obtained in the two NUC points and in the temperature range between the two NUC points, the spatial noise is < 60% of the temporal noise in the whole temperature range (Figure 4a). Even after several temperature cycles of the array, only a minor increase of the spatial noise is observed. This stability and image correctability in such a large temperature span indicates that both the detector material and the ROIC are very robust, with a linear behavior in a very large dynamic range. Excellent temporal image stability is also observed, with no deterioration of the image quality (spatial noise) with time during a two hour long measurement (Figure 4b). The long term stability of the NUC calibration of these 320 x 256 MWIR FPAs has also been studied by ONERA [8], by comparing the Residual Fixed Pattern Noise (RFPN) with the temporal noise (TN). Measurements of RFPN and TN were performed twice a day over a three week period of time (Figure 4c). For each measurement, gain and offset corrections were applied on each pixel, using the gain-offset tables determined the first day (D0). The correction was considered as still valid, as long as the RFPN was lower than the temporal noise (TN) measured at a given day. In this study, the correction was deemed as valid even after three weeks of measurements. This gives proof to the excellent stability over time of these detectors, comparable to QWIP behavior.

The fourth measure, which was used to study the reproducibility of the FPAs is the pixel operability. Three criteria are used to define if the pixel is non-operable [9]: 1) if its signal output level is not within ± 30% of the mean signal level, 2) if the NETD is not within ± 100% of the mean NETD or 3) if the response is not within ± 20% of the mean responsivity. Statistics from the operability of the Volatile Organic Compound (VOC) FPAs [10] is shown in Figure 5. The majority of the arrays have operabilities in the range 99.8 – 99.9%, with an average operability of 99.87%. This is approximately comparable to the operability of QWIPs, which are known for their high operability, good uniformity and good manufacturability [11]. The combined results from the studies
of the reproducibility, stability and operability of the type-II InAs/GaSb SL FPAs shows that this indeed is a mature technology that is competitive to other state-of-the-art IR detectors such as HgCdTe, InSb and QWIPs.

In summary, the performance of type-II InAs/GaSb superlattice detectors and FPAs has been studied. Temperature dependence studies of a single pixel device showed that the dark current increases from $2 \times 10^{-9}$ A/cm$^2$ at $T = 80$ K to $2 \times 10^{-3}$ A/cm$^2$ at $T = 170$ K and that the dark current is diffusion limited for temperatures $> 110$K. An increase of the peak quantum efficiency from 37% at 70 K to 51% at 110 K was observed, which was attributed to limited diffusion length. From statistics of a multitude of manufactured FPAs, average temporal and spatial NETD values of 12 mK and 4 mK, respectively, were deduced and the average operability of the FPAs is 99.87%. Furthermore, it has been shown that the image stability after NUC calibration of the FPAs is very good, with a maintained ratio of 0.4 between spatial and temporal NETD for at least two hours within one cooldown and that this ratio stays below 0.6 even after several temperature cycles.


Figure captions:

Figure 1. (a) Detector quantum efficiency in the temperature range T = 70-150 K at an applied bias of -50 mV (b) Temperature dependence of the peak QE value (@ 3.4 μm) at an applied bias of -50 mV (c) Measured absorption quantum efficiencies in the temperature range 80-140K.

Figure 2. (a) Measured dark current density in the temperature range T = 80 – 170 K. (b) Curve fits of dark current density components: diffusion (J_diff), generation-recombination (J_GR) and trap assisted tunneling (J_TAT) to the dark current density measured at 110K. (c) Arrhenius plot of the dark current density versus inverse temperature, measured at – 50 mV. Activation energy of the diffusion current of 236 meV was deduced from a linear fit to the Arrhenius plot in the high temperature regime (T ≥ 120K).

Figure 3. (a) Statistics of temporal and spatial NETD values of InAs/GaSb FPAs manufactured by IRnova, showing an average temporal NETD of 12 mK and an average spatial NETD of 4 mK. (b) Histogram of the temporal noise in an FPA showing a very narrow distribution of the NETD values within the array both when presented in linear scale (black, left axis) and logarithmic scale (grey, right axis).
Figure 4. (a) Ratio of spatial/temporal NETD of an InAs/GaSb FPA as measured immediately after NUC calibration for very high instantaneous signal dynamic and after one and two temperature cycles. (b) Stability of the ratio between spatial and temporal NETD values within one cool-down. (c) Ratio of residual fixed pattern noise/temporal noise of an InAs/GaSb FPA measured over a three week period, using the initial NUC calibration performed on the first day (D0) in each measurement. Measurements were performed by ONERA [8].

Figure 5. Statistics of the operability of InAs/GaSb FPAs manufactured at IRnova, showing an average value of the operability of 99.87 %.
(a) Spatial / temporal NETD

(b) Image stability

(c) RFPN Temporal noise

Blackbody temperature (°C)
Highlights:

- Statistics of the operability and the NETD of more than 70 manufactured InAs/GaSb type II superlattice FPAs are presented.
  
  o A mean operability of 99.87% is observed.
  
  o The mean temporal and spatial NETD values observed are 12 mK and 4 mK, respectively.

- Excellent long term stability of an InAs/GaSb FPA is presented. The ratio of residual fixed pattern noise and temporal noise stays below 0.6 after 3 weeks of testing with temperature cycling every day.

- Good single pixel performance was observed with dark current densities of $1 \times 10^{-6}$ A/cm$^2$ and quantum efficiencies of 53% at 120 K.