High Performance 15- μm Pitch 640×512 MWIR InAs/GaSb Type-II Superlattice Sensors

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Abstract—We report the high performance of Mid-wave Infrared Region (MWIR) InAs/GaSb Type-II Superlattice (T2SL) sensors with 640×512 format and 15- μm pixel pitch at both Focal Plane Array (FPA) and pixel level. The p-intrinsic-Barrier-n epilayer structure is adopted for this study, which is grown on $620 \pm 30 \mu\text{m}$ thick GaSb substrate and highly-doped GaSb cap layer at the top structure. The mesa type pixels with sizes of $220 \mu\text{m} \times 220 \mu\text{m}$ have dark currents $7.8 \times 10^{-12} \text{ A}$ at 77 K both of which are equivalent to state-of-the-art values for Type-II Superlattice sensors. The various passivation techniques to lower the dark current are applied and the results are given in terms of dark current. Electro-optical measurements yielded comparable results to literature. After gathering data and optimizing the fabrication conditions, the FPA of 15- μm pitch having 4.92 μm cut-off wavelength (λ_c) shows 1.6 A/W peak responsivity, Noise Equivalent Temperature Difference (NETD) of 22.6 mK with optics of f/2.3, quantum efficiency larger than 65% and 99.75% operability. The acquired images by using aforementioned FPA device is presented in this paper. With the reduction of dark current, an encouraging imaging performance is obtained which shows the potential of the Type-II Superlattice detectors in 3rd generation infrared sensors.

Index Terms—Infrared photodetectors, focal plane array, MWIR, InAs/GaSb, type-II superlattice.

I. INTRODUCTION

HIGH thermal contrast, high sensitivity, large format detectors with high uniformity, small pixel size, high operability, high-temperature operation, low cooling and power requirements, multi-spectral operations, and low cross-talk are the requirements of the 3rd generation IR systems.

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The common commercial FPAs such as MCT, InSb, and QWIPs suffer from high cost, missing large area lattice matched substrates for MCT, low quantum efficiency for QWIPs and fixed band gap for InSb. Therefore, the necessities of 3rd generation IR systems should be satisfied with relatively new type of device structure where InAs/GaSb T2SLs stand out as suitable candidates for this position. The robustness of material, the ability to operate almost in entire infrared region, the weak dependence of band gap on the operating temperature, and having close lattice constants properties of Sb-based materials make InAs/GaSb Type-II superlattices outstanding candidates for new generation IR systems. After Esaki and Tsu [1] in 1970 proposed first superlattices, the idea of broken bandgap and Type-II superlattices were considered as new infrared imaging approaches in between 1977-1979. The idea is based on the location of conduction and valence band edges in different material, resulted in that the wave functions of the highest valence subband and the lowest conduction subband are located in two-distinct-semiconductors. The conduction and the valence band edges can be tuned independently with this structure.

The recent developments since 2006 have focused on reducing dark current, increasing quantum efficiency, and fabrication of large format, small pixel size arrays. Heterojunction detector designs have arisen such as nBn [2], pBp [3] and Xbn [4] designs. Moreover, besides the single band nBn detectors [5], dual-band nBn detectors [6] and pBn detectors [7], double heterojunction structures like [8], [9], p- π -M-n detectors [10], PbIbN structure [11], and CBIRD design [12] have been popular designs for superlattice structures. The complex superlattice cell designs have combined with heterojunction designs, either as a barrier or as an absorber, and they were named as W and M shapes. In 2005 Walther *et al.* [13] demonstrated the first superlattice FPA which is a 40- μm -pitch 256×256 MWIR (λ_c of 5.4 μm) FPA with 11.1 mK NETD (f/2 optics) for integration time of 5 ms, 30% quantum efficiency, 10^{13} Jones detectivity at $T=77 \text{ K}$. In 2007, different groups showed their FPAs like Fraunhofer IAF (4.9 μm cut-off, 27.9 mK NETD) [14], NWU (25 μm pitch, 320×256 , 12 μm cut-off, 340 mK NETD) [15], JPL and Raytheon (256 $\times$ 256, 10.5 μm cut-off, p-i-n) [16]. In 2008, Kim *et al.* [17] demonstrated 256 $\times$ 256 MWIR FPA with an nBn design. In the same year, Plis *et al.* manifested 24 μm pitch 320×256 FPA which has 4.2 μm λ_c , 23.8 mK NETD with integration time of 16.3 ms and f/4 optics [18]. In 2011, dual color (dual band) FPAs in 288 $\times$ 384 format and 40 μm

pitch was presented by Walther *et al.* [19]. The heterojunction designed 640×512 , $15 \mu\text{m}$ pitch FPA ($5 \mu\text{m}$ cut-off, 65% quantum efficiency, at -0.05 bias and 120 K , $3 \times 10^{-6} \text{ A/cm}^2$ dark current density, 41 mK at 90 K with 21 ms integration time, and $f/4$ optics) was fabricated in 2013 by Martijn *et al.* [20]. In 2014, Katayama and others [21] showed their FPA ($6 \mu\text{m}$ cut-off, 320×256 , $30 \mu\text{m}$ pitch, 250 mK NETD with optics of $f/2.3$ and $200 \mu\text{s}$ time of integration at 77 K). Razeghi and co-workers [22], in 2015, presented pMp design T2SL FPA ($27 \mu\text{m}$ pitch in 320×256 format, 2.4 A/W peak responsivity at $4.2 \mu\text{m}$ with 68.6% quantum efficiency, detectivity 3.5×10^{11} Jones, NETDs 11 mK and 15 mK at 81 K and 110 K , respectively). In 2016, a FPA which had following properties: p-i-n design, 320×256 format, $30 \mu\text{m}$ pitch, $4 \times 10^{-7} \text{ A/cm}^2$ dark current at 77 K with -20 mV bias, 31 mK NETD ($f/2.3$ optics) at 77 K with integration time of 1.2 ms presented by Miura *et al.* [23]. 99% operability, 1.2 A/W responsivity at $4.1 \mu\text{m}$ wavelength, and $4.1 \times 10^{12} \text{ cm/Hz}^{1/2}$ detectivity were obtained. In 2017, Jenkins *et al.* [24] (2.4 -megapixel, $5.1 \mu\text{m}$ cut-off, $5 \mu\text{m}$ pitch, $3 \times 10^{-5} \text{ A/cm}^2$ median dark current, operability larger than 99.9% and quantum efficiency $> 60\%$) and Sharifi *et al.* [25] ($10 \mu\text{m}$ pitch, $2\text{k} \times 2\text{k}$, $3 \times 10^{-5} \text{ A/cm}^2$ dark current with $5.11 \mu\text{m}$ λ_c , $2 \times 10^{-6} \text{ A/cm}^2$ with $\lambda_{\text{c of}}$ of $4.6 \mu\text{m}$) showed their works. Sharifi *et al.* [25] also reported $5 \mu\text{m}$ pitch FPA results, $6.3 \times 10^{-6} \text{ A/cm}^2$ at 150 K with $5 \mu\text{m}$ cut-off wavelength having $\sim 50\%$ quantum efficiency with 20 mK NETD at 150 K .

In this work, we present 640×512 format $15\text{-}\mu\text{m}$ pitch InAs/GaSb Type-II Superlattice sensors with a high performance at both Focal Plane Array (FPA) and pixel level.

II. FABRICATION OF T2SL FPA

We have fabricated and characterized both large area diodes and FPAs. The fabrication steps of T2SL sensors are the same as presented in Ref. [25], and hence are not duplicated in this paper. However, the highlights of both large area pixel diode and FPA fabrication are underlined to a certain extent, of which the results are presented herein.

The p-i-B-n form of superlattice multilayer structure, having $4.92 \mu\text{m}$ cut-off wavelength, is used for this study grown on GaSb substrate. By using piBn structure, it is aimed to utilize relatively higher mobility of electrons for collection efficiency of p-type absorber layer. In order to reduce surface leakages, barrier layer is inserted to the structure. Large area diodes are fabricated in a $220 \mu\text{m} \times 220 \mu\text{m}$ size. Both FPA and large area samples are etched with a citric acid ($\text{C}_6\text{H}_8\text{O}_7$) based solution. The thin ohmic contact layers of Ti/Au are formed with electron beam deposition technique. For the passivation of pixels, methods and materials which are differing from each other either by deposition technique like electron beam physical vapor deposition and plasma enhanced chemical vapor deposition (PECVD) or by processing conditions like in polyimides by curing and without curing are investigated. Yielded results of differently passivated samples were compared with unpassivated large area diode in Ref. [26]. According to previous study, polyimide passivation has shown relatively lower dark current than the

Fig. 1. The comparison of different passivation methods/materials in terms of dark currents at 77 K .

other passivation methods investigated in detail. However, the long term stability of polyimide passivation is unknown. Therefore, in this study, the dark current characteristics of low temperature SiO_2 passivation was analyzed for T2SL FPAs. The fabrication of large area samples are completed at this step whereas FPA fabrication continued with another metalization step as depositing Ti/Ni/Au layers using e-beam technique. The $8 \mu\text{m}$ -tall-indium bumps are also deposited with thermal evaporation technique by optimizing the In grain sizes. After the FPA is diced according to the read-out integrated circuit (ROIC), FPA is bonded by flip-chip bonding technique with ASEL64015 ROICs [27] from ASEL SAN. The low-stress and cryogenically resistant epoxy is injected. The $\sim 640 \mu\text{m}$ -thick GaSb substrate is, then, mechanically thinned to several tens of μm by grinding. Then, T2SL FPA-ROIC hybrid is wirebonded. Large area pixel diodes are not hybridized with any ROIC. They are directly bonded to leadless ceramic chip (LCC) for electrooptical characterization.

III. RESULTS & DISCUSSION

The fabricated large area diodes and FPAs are characterized either in the sense of dark currents or NETD levels. The same fabrication procedure is followed for all samples on same T2SL wafer with same etch depth and same ohmic contact formations. All the dark current measurements are performed at LN2 temperature of 77 K and are given in **Figure 1**. The results are given as an average of 20 single diodes on each sample and there is no significant change/variation for samples of each trials.

We have studied various alternative passivation materials/conditions. Dark currents levels for all passivation methods show no significant difference ($1.5 \times 10^{-11} \text{ A}$ for cured-polyimide and $1.3 \times 10^{-11} \text{ A}$ for PECVD SiO_2 at -0.1 V bias). In our previous work, polyimide has been chosen as the best passivation material based on investigation of the dark currents. However, the long-term stability of polyimide films, especially at cryogenic temperatures, is unknown. Therefore, the low temperature PECVD SiO_2 passivation is examined on the samples which are fabricated on same wafer as polyimide passivated ones. The low temperature SiO_2 passivated large

Fig. 2. NETD histograms for 640 $\times$ 512 T2SL FPA.

area diode gives the lowest dark current, 7.8×10^{-12} A at -0.1 V bias voltage. This dark current is almost 2/3 of the dark current of polyimide passivated diode.

After the additional characterization of these large area diodes, low temperature SiO_2 is chosen as a passivation material for FPA fabrication. T2SL FPAs are fabricated in accordance with the previously mentioned fabrication cycle and FPA level characterizations are performed. The NETD histogram and NETD map of fabricated FPA are given in **Figure 2** and **Figure 3**.

Utilizing 0.18 μm -CMOS process, ASELSAN designed and fabricated ASEL64015 ROIC for MWIR applications. Having properties of programmable pixel gain with adjustable full-well-capacity (FWC) (to 4.5 Me-, 9 Me- and 13.5 Me-) for a Direct Injection (DI) input stage, controlling biasing voltage values and all analog current through a digital interface make ASEL64015 ROIC easy to use. With internal timing circuitry, the resolution of 0.1 μs can be reached for programming the integration time. Single, double and quadruple output modes of ROIC show 120 frames-per-second (fps). The ROIC is also designed for Integrate-While-Read (IWR) and Integrate-Then-Read (ITR) modes in snapshot operation. By changing the common-gate input stage at the input of DI pixel, the control of photodetector reverse bias voltage is provided.

Fig. 3. NETD map of 640 $\times$ 512 T2SL FPA.

Fig. 4. Noise histogram for 640 $\times$ 512 T2SL FPA.

The detector common voltage is produced a voltage regulator having features of an on-chip and low-dropout. It is also possible to operate ROIC for smaller format and larger pixel-pitch detectors like 320 $\times$ 256 format and 30 μm by 2×2 binning property [28].

At 50% well filling of ROIC capacitors (4.5 Me), 25 FPS and 2 ms integration time, the FPA offers an average NETD of 22.6 mK (median 22.8mK) $f/2.3$ optics. The NETD measurements performed with large area body between 300K and 310K temperatures. While a lens is not used during the measurements optical aperture is adjusted with cold stops. The NETD histograms are fairly symmetric when examined in both linear and semilog scales. We attribute this to uniform response and significantly photo-current limited operating regime. This level of NETD for such FPA is comparable to values reported in literature, and it is a very promising result. The noise characteristics of FPA is also investigated in digital level and the noise histogram for FPA is given in **Figure 4**.

Fig. 5. Bad pixel map of 640×512 T2SL FPA.

Fig. 6. Images acquired by a 640×512 MWIR type-II superlattice detector.

The average noise is 4 digital levels with a FWHM of 2 digital levels. The noise distribution is very similar to NETD distribution, which is narrow, symmetric and without any tail corresponding to uniformity in noise. When the noise characteristics of ROIC integrated FPA is investigated, it is found that the noise comes substantially from test setup (3.2 digital levels) which is performed by acquiring data at very low integration times and comparing it with the data at the operating integration time.

It is observed on the NETD map that there is a slightly lower NETD region around the edges of the array. The pixels in this region exhibits slightly higher responsivities at same dark current levels, resulting a slightly lower NETD values. Although we have not performed detailed investigation of this behavior our initial hypothesis suggest that this is an effect caused by mechanical stress at cryogenic temperatures since the pattern correlates to our expected stress distribution over the array and appears much more strongly after application of underfill epoxy.

In **Figure 5**, bad pixel map of 640×512 T2SL FPA is given. The pixels are marked as bad pixels that yield 30% higher and/or lower responsivity than the mean responsivity and higher noise than 6 digital level. The bad pixel ratio of detector is found to be 0.25% and hence the operability is found to be at least 99.75%. After optimizations in fabrication processes according to the characterization data, the final version of 640×512 $15\text{-}\mu\text{m}$ pixel pitch MWIR type-II superlattice FPA is fabricated. Two example images acquired by this FPA are presented in **Figure 6**.

The images shown in **Figure 6** are recorded with lens having f-number of 2.3 and integration time of 2 ms at 60 mV reverse bias and 77 K. The cut-off wavelength for this detector is $4.92\text{ }\mu\text{m}$. The responsivity is calculated as 1.6 A/W with quantum efficiency (η) $> 65\%$ without anti-reflection. The quantum efficiency value is estimated using the responsivity of the pixel on the array, known charge capacity of the ROIC and spectral response of the material measured on large area detectors.

IV. CONCLUSION

Large format 640×512 , $15\text{-}\mu\text{m}$ pitch InAs/GaSb T2SL sensors with good performance at both FPA and pixel level are demonstrated in this paper. After characterizations at large area pixel level for dark current of different passivating approaches, low temperature grown SiO_2 is chosen. After integration with the ROIC, image acquisition with $15\text{-}\mu\text{m}$ pitch, 640×512 T2SL FPA for mid-IR is demonstrated. The image is obtained by using f/2.3 optics at 2 ms integration time, 60 mV reverse bias and a temperature of 77 K. The detector is shown to possess sharp NETD and noise histograms, a highly uniform NETD pixel map, an average responsivity of 1.6 A/W, an average quantum efficiency $> 65\%$, an average NETD of 22.6 mK at 77 K and $> 99.75\%$ operability.

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