Mid-IR focal plane array based on type-II InAs/GaSb strain layer superlattice detector with nBn design

H. S. Kim,1 E. Plis,1 J. B. Rodriguez,1,a) G. D. Bishop,1 Y. D. Sharma,1 L. R. Dawson,1 S. Krishna,1,b) J. Bundas,2 R. Cook,2 D. Burrows,2 R. Dennis,3 K. Patnaude,2 and M. Sundaram2

1Center for High Technology Materials, Department of Electrical and Computer Engineering, University of New Mexico, Albuquerque, New Mexico 87106, USA
2QnagsQ LLC, One Tara Boulevard, Suite 102, Nashua, New Hampshire 03062, USA

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A midwave infrared camera (λc = 4.2 μm) with a 320 × 256 focal plane array (FPA) based on type-II InAs/GaSb strain layer superlattice (SLs) has been demonstrated. The detectors consist of an nBn heterostructure, wherein the SL absorber and contact layers are separated by a Al0.2Ga0.8Sb barrier layer, which is designed to have a minimum valence band offset. Unlike a PN junction, the size of the device is not defined by a mesa etch but confined by the lateral diffusion length of minority carriers. At 77 K, the FPA demonstrates a temporal noise equivalent temperature difference (NETD) of 23.8 mK (Tint = 16.3 ms and Vref = 0.7 V) with a peak quantum efficiency and detectivity at 3.8 μm equal to 52% and 6.7 × 1011 Jones, respectively. © 2008 American Institute of Physics. [DOI: 10.1063/1.2920764]

Midwave-infrared (MWIR) focal plane arrays (FPAs) are widely used for a variety of imaging applications, including medical diagnostics and terrestrial surveillance. State-of-the-art detectors are based on interband transitions in PN junctions made from either InSb or HgCdTe (MCT) on inter-subband transitions in quantum well IR (QWIP) detectors. However, lack of spatial uniformity over a large area still plagues InSb and MCT devices, while QWIPs have larger dark currents and lower quantum efficiency (QE) compared to the interband devices. Type-II InAs/GaSb superlattices (SLs) for IR detection were first proposed by Smith and Mailhiot in 1987.

Since then, SL based detectors have been considered as an alternative technology for the fabrication of high performance FPAs. The effective band gap of the InAs/InGaSb SLs can be tailored from 3 to 30 μm by varying thickness of constituent layers thus allowing fabrication of devices with operating wavelengths spanning the entire IR region. Moreover, normal incidence absorption is permitted in these structures resulting in high QE. Commercial availability of low defect density substrates and a high degree of uniformity for III-V processing over a large area also offers technological advantages for the SLs. In addition, detector performance at high temperature is expected to be improved because of a comparatively large effective electron mass (~0.04m0) that enables SLs to suppress tunneling effect, and Auger recombination processes.2 This makes SLs an attractive technology for realization of high performance third generation FPAs.

Presently, all SL detectors are based on a photodiode design. In this case, the optically active area of the photodiode is defined by an etched mesa. During the mesa isolation process, the periodic nature of the idealized crystal structure abruptly ends at the mesa lateral surface. Disturbance of the periodic potential function due to a broken crystal lattice leads to allowed electronic quantum states within the energy band gap of SLs resulting in large surface leakage currents. The suppression of these currents is the most demanding challenge for present day SL technology, especially for long wavelength IR and very long wavelength IR spectral regions, since the dimensions of SL pixels have to be scaled to ~20 μm in FPAs. In order to overcome the limitation imposed by surface leakage currents, a stable surface passivation layer is needed. So far, various approaches have been proposed such as the deposition of polyimide layer,3 overgrowth of wide band gap material,4 deposition of passivating sulfur coating electrochemically,5 and post-etch treatment in chemical solutions.6 However, these passivation methods are either sensitive to the cutoff wavelength of the device or complicates the fabrication process of FPAs.

Recently, a nBn structure has been proposed to effectively suppress the surface leakage current and increase the operating temperature of InAs based detectors.7 The nBn detector with InAs and InAsSb materials have shown that the background limited IR photodetection temperature can be increased by 100 K. The nBn structure is composed of an n-type narrow band gap absorber layer with a wide band gap undoped barrier layer which is chosen to have a minimal valence band offset. This is then sandwiched between the top and bottom contacts. The band structure of the nBn design is shown in Fig. 1(a). The majority carrier (electron) current is blocked by a large conduction band offset whereas minority carriers (holes) freely move between the electrodes. Hence, the optically active area of nBn detector is defined by the diffusion length of minority carriers and not by the dimensions of the etched mesa. It is important to note that there is no surface leakage current in these devices since the individual pixels are not separated by an etched mesa. Recently, single pixel detectors based on the nBn structure with InAs/GaSb SLs as the n-type narrow band gap layer and an AlGaSb barrier layer have been reported.8 In this paper, we report on the fabrication of a 320 × 256 FPA based on this design with a cutoff wavelength of 4.2 μm operating at 77 K.
Detector samples were grown on Te-doped epiready (100) GaSb substrates using a solid source molecular beam epitaxy VG-80 system. The system was equipped with SUMO® cells for gallium and indium and a standard effusion cell for aluminum and cracker cells for antimony and arsenic. The growth details were reported elsewhere. The detector structure consists of nominally undoped 100 nm thick Al$_{0.2}$Ga$_{0.8}$Sb etch stop layer followed by a 360 nm bottom contact layer formed by 8 ML InAs$_n$:Si$_{1000}$ cm$^{-3}$/8 ML GaSb SLs. Then a 2.4 μm thick unintentionally doped absorber formed by 8 ML InAs/8 ML GaSb SLs were grown followed by a 100 nm thick Al$_{0.2}$Ga$_{0.8}$Sb barrier layer. The SL absorption region is residual $n$-type with a carrier concentration in the low $10^{16}$ cm$^{-3}$ at room temperature. The structure was terminated by a 100 nm $n$-type ($n=4\times10^{18}$ cm$^{-3}$) top contact layer. The heterostructure schematic is presented in the Fig. 1(b).

Each processed FPA die consists of $320\times256$ pixels with a 30 μm pitch. On a quarter of a 2 in. GaSb wafer two FPAs were realized, each with an area of $10.34\times8.97$ mm$^2$. Processing was initiated by defining $24\times24$ μm$^2$ squares with standard UV photolithography and a shallow wet chemical etch using phosphoric acid was performed. It is to be noted that the depth of the shallow etch was equal to 0.15 nm, which corresponds to the middle of the barrier layer. Thus, the active absorber layer underneath is untouched. Then an inductively coupled plasma dry etch to the middle of the bottom contact layer on the three outermost rows and columns of the FPA was undertaken. A scanning electron microscope (SEM) image of a part of a fully processed FPA is shown in the Fig. 1(c) and illustrates the two steps of the etching process. Top and bottom contacts were then deposited using an electron beam metal evaporation system. We used Ti/Pt/Au 500/500/3000 Å as contact metals for both top and bottom Ohmic contact metallization. Finally, to enable well defined indium bumps, an under bump metal (UBM) deposition was conducted using Ti/Ni/Au (300/1500/500 Å). Indium bumps with a thickness $\sim3$ μm were thermally evaporated on UBM metal pads. Following this, the FPAs were hybridized to ISC0209 read-out integrated circuits (ROICs) made by Indigo.

FIG. 1. (a) Band structure schematic of an $nBn$ structure under applied bias. (b) The heterostructure schematic of $nBn$ device. (c) SEM image showing part of fully processed FPA with deposited indium bumps. The two-step etch process is illustrated.

FIG. 2. Histogram of the NEDT distribution in the FPA for an integration time of 16.3 ms with $f$/2.3 optics.

100 nm $n$-type ($n=4\times10^{18}$ cm$^{-3}$) top contact layer. The heterostructure schematic is presented in the Fig. 1(b).
External QE of FPA was obtained using the spectral response curve from the test diode on the FPA chip with $380 \times 380 \, \mu m^2$ optical area. Spectral measurements were performed using a Fourier transform IR spectrometer (FTIR). Under 0.7 V bias and at 77 K, the FPA exhibits a QE as high as 52% at 3.8 $\mu m$ [Fig. 3(a)]. Peak responsivity and detectivity of FPA were estimated, respectively, to 1.6 A/W and $6.7 \times 10^{11}$ Jones at 3.8 $\mu m$ and 77 K ($V_b=0.7$ V). Values of specific detectivity as a function of wavelength are presented on the Fig. 3(b).

A thermal image taken with $320 \times 256$ MWIR FPA camera based on InAs/GaSb SLs at a detector temperature of 77 K and an integration time of 16.3 ms is shown in Fig. 4. Two point nonuniformity correction (NUC) was used for the imaging. Temperatures of 20 and 40 °C were utilized as the low and high temperature for the NUC correction algorithm. The bright areas of the image represent warmer regions whereas the dark areas exhibit colder regions. In the figure, the thermal imprint of the cold can is clearly visible demonstrating the good imaging quality of thermal imager.

In conclusion, we demonstrated $320 \times 256$ FPA based on type II InAs/GaSb SLs with $nBn$ detector design. Average value of dark current density ($1 \times 10^{-7}$ A/cm²) at 77 K ($V_b=0.7$ V) is comparable to that reported for the state-of-the-art MWIR SL photodiodes utilizing some passivation schemes. At 77 K, FPA reveals a cutoff wavelength of 4.2 $\mu m$ and NETD of 23.8 mK for 16.3 ms integration time. Peak responsivity and detectivity of FPA were estimated, respectively, to 1.6 A/W and $6.7 \times 10^{11}$ Jones at 3.8 $\mu m$ and 77 K.

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**References**