Molecular beam epitaxy growth and characterization of type-II \text{InAs/GaSb} strained layer superlattices for long-wave infrared detection

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The authors report on investigation of type-II \text{InAs/GaSb} and \text{InAs/InGa\textsubscript{1−x}Sb} strained layer superlattices (SLSs) for long-wave infrared detection. Growth conditions were optimized to obtain nearly lattice matched ($\Delta a/a \sim 0.03\%$) 13 ML \text{InAs}/7 ML \text{GaSb} SLS nBn detector structure with cutoff wavelength of $\sim 8.5$ $\upmu$m (77 K). Dark current density was equal to $3.2 \times 10^{-4}$ A/cm$^2$ ($V_b = +50$ mV, 77 K) for this detector structure. Thin 10 ML \text{InAs}/6 ML \text{In\textsubscript{0.33}Ga\textsubscript{0.67}Sb} SLS was grown with zero lattice mismatch achieved by incorporation of 2.5 ML of GaAs in every SLS period.

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I. INTRODUCTION

Photodetectors operating in the long-wave infrared (LWIR, 8−14 $\upmu$m) spectral band are of great importance for military and commercial applications of infrared (IR) thermal imaging. It includes satellite-based surveillance, atmospheric pollution probes, and astrophysical imaging, to name a few. Detectors based on mercury-cadmium-telluride (MCT) (Hg\textsubscript{1−x}Cd\textsubscript{x}Te) material system have been the dominant IR technology for such applications. However, the low-band gap MCT alloys are sensitive to small changes in the alloy composition ratio, and poses short lifetimes due to strong Auger recombination rates. Moreover, MCT detectors are characterized by low electronic mass resulting in excessive dark current due to tunneling.\textsuperscript{1}

Since first proposed in the 1980s (Refs. 2 and 3) \text{InAs/(InGa)Sb} strained layer superlattices (SLSs) promise a number of advantages over MCT alloys in LWIR mode. These heterostructures are characterized by the broken-gap type-II alignment, with electrons and holes localized in \text{InAs} and (In,Ga)Sb layers, respectively. The overlap of electron (hole) wave functions between adjacent \text{InAs} (In,Ga\textsubscript{1−x}Sb) layers results in the formation of electron (hole) minibands in the conduction (valence) band. Optical transition between the highest hole (heavy hole) and the lowest conduction minibands is employed for the detection of incoming IR radiation. The effective band gap of the \text{InAs/(InGa)Sb} SLSs can be tailored from 3 to 30 $\upmu$m by varying thickness of constituent layers thus allowing fabrication of devices with operating wavelengths spanning the entire IR region. The SLSs are less sensitive to the compositional nonuniformities in the ternary layer than the MCT alloys with the same band gap. For instance, compositional ratio fluctuation of $\Delta x = 0.004$ would shift cutoff wavelength of MCT detector from 19 to 17 $\upmu$m, whereas the corresponding ratio change for SLS is $\Delta x = 0.03$.\textsuperscript{4}

The thin SLS constituent layers provide a good electron-hole overlap, with the optical matrix elements comparable to those of bulk MCT. (In,Ga)Sb layers of SLS are subjected to biaxial compression causing splitting of light hole and heavy-hole minibands in the SLS band structure. Therefore, Auger recombination rates are strongly suppressed relative to bulk MCT (Refs. 5 and 6) leading to improved temperature limits of spectral detectivities compared to MCT detectors.\textsuperscript{7} In addition, the larger effective mass in SLS leads to a reduction in tunneling currents.

In order to extend detector cutoff wavelength into LWIR and very-long wave infrared (VLWIR) regions, two approaches based on \text{InAs/(InGa)Sb} SLS have been studied in the past. They are (1) binary-binary (InAs/GaSb) and (2) binary/ternary (InAs/In\textsubscript{0.33}Ga\textsubscript{0.67}Sb) SLS. While theoretical predictions seem to favor the \text{InAs/GaSb} system due to the additional strain provided by the \text{InGaSb} layer, most of the experimental results in the past 5 years have been on the binary \text{InAs/GaSb} system.

In this article, we report on LWIR detectors based on \text{InAs/GaSb} SLS system. We also present some preliminary results on the SLS ternary system. This article is organized as follows: First, conditions of strain-balanced SLS growth were investigated for both binary-binary and binary-ternary SLS. In lattice mismatch systems, when the thickness of epilayer exceeds the critical value, strain caused by lattice mismatch of epilayer to the substrate is relived by formation of threading dislocations.\textsuperscript{8} Performance of IR detectors is strongly affected by the presence of threading dislocations which play role of scattering centers for minority carriers thus degrading the signal-to-noise ratio of the detector. Therefore, it is important to match lattice constants of SLS and the substrate in order to prevent formation of threading dislocations. Since the lattice constant of \text{InSb} (GaSb) is much larger (smaller) than that of GaSb, insertion of few monolayers of these materials into the SLS stack leads to changing in SLS lattice constant to some extent and helps to...
achieve the zero mismatch between SLS and GaSb substrate.\textsuperscript{9,10,47} Next, LWIR detector ($\lambda_{\text{cutoff}} \sim 8 \, \mu m$) based on optimized InAs/GaSb SLS is demonstrated. Finally, our efforts to extend operating wavelength into LWIR region using InAs/In$_{x}$Ga$_{1-x}$Sb SLS are reported.

\textbf{A. Present status of InAs/GaSb SLS and InAs/(In,Ga)Sb Sb detectors}

Relative simplicity of binary-binary SLS growth in combination with advantages of InAs/(In,Ga)Sb SLS system makes InAs/GaSb SLS very attractive material for realization of IR detectors with cutoff wavelength of 11 $\mu m$ and beyond.\textsuperscript{11–15} Physical and optical properties of InAs/GaSb SLS, in particular, band gap variation as a function of SLS period thickness, mobility, and lifetime of minority carriers were studied theoretically\textsuperscript{16,17} and experimentally\textsuperscript{18–21} Figure 1(a) illustrates calculated values of cutoff wavelengths for InAs/GaSb SLS as a function of constituent layer thickness using pseudopotential method.\textsuperscript{46}

Electronic and optical properties,\textsuperscript{22–25} as well as fundamental characteristics (effective mass,\textsuperscript{26} minority carrier lifetime,\textsuperscript{27} and electron mobility\textsuperscript{28}) of InAs/In$_{x}$Ga$_{1-x}$Sb SLS were investigated by different research groups.

Design parameter space of InAs/In$_{x}$Ga$_{1-x}$Sb SLS includes thickness of InAs ($n$) and InGaSb ($m$) layers as well as mole fraction of In in In$_{x}$Ga$_{1-x}$Sb layers ($x$). There are numerous combinations of $m$, $n$, and $x$ which will yield an InAs/In$_{x}$Ga$_{1-x}$Sb SLS with specific cutoff wavelength, but only few of them will result in strong electron-hole overlap. In 1990s, substantial efforts were devoted to theoretical studies of SLS parameters for optimum absorption in InAs/In$_{x}$Ga$_{1-x}$Sb SLS material. Heller et al.\textsuperscript{29} reported optimized linear absorption coefficients for InAs/In$_{x}$Ga$_{1-x}$Sb SLS based on a model envelope-function approach at 10, 15, and 20 $\mu m$. Using a modified bond orbital model (EBOM) the SLS design parameters that give the best optical absorption within wide wavelength range were defined. $M$, $n$, and $x$ triples that bestow the maximum oscillator strength for $\lambda_{\text{cutoff}} = 15 \, \mu m$ are shown in Fig. 1(b). As shown in Fig. 1(b), long-wave detection can be achieved with thicker InAs and In$_{x}$Ga$_{1-x}$Sb layers with smaller In content. However, detectivity of such devices is expected to be lower because of reduced spatial matrix element. With an increase in the In mole fraction $x$, the thickness of both constituent layers required to get the same cutoff wavelength decreases. This is attributed to the upward shift of In$_{x}$Ga$_{1-x}$Sb heavy-hole band due to larger compressive strain in In$_{x}$Ga$_{1-x}$Sb layers with subsequent reduction in SLS band gap allowing thinner layers for realization of the same cutoff wavelength.

Despite expected advantages of InAs/In$_{x}$Ga$_{1-x}$Sb SLS for optoelectronic applications, very few reports of lasers and photodetectors based on this material system have been published. We can see two reasons for that: first, the sensitivity of the narrow energy gap SLSs to small changes in the individual layer thicknesses.\textsuperscript{31} EBOM predicted that the submonolayer thickness fluctuations can change the cut-off wavelength by 50% or more, especially for VLWIR region. However, with three-band envelope-function model it was shown\textsuperscript{40} and later proven experimentally\textsuperscript{41} that those monolayer fluctuations of the InAs and In$_{x}$Ga$_{1-x}$Sb layer thickness would shift the cutoff wavelength insignificantly.

Second, it was shown\textsuperscript{31} that the electron-hole overlap and associated oscillator strength increase with $x$. The growth of In$_{x}$Ga$_{1-x}$Sb layers with large mole fraction of In may be challenging due to critical thickness limitations imposed on strained material.

\textbf{II. EXPERIMENT}

\textbf{A. Growth details (InAs/GaSb SLS and InAs/In$_{x}$Ga$_{1-x}$Sb SLS)}

The structures presented in this article were grown in a VG-80 solid-source molecular beam epitaxy system on $n$-type (Te doped with $n \sim 5 \times 10^{17} \, \text{cm}^{-3}$) epiready (001) GaSb double-side polished substrates using valved As and Sb cracker sources, and Ga and In SUMO$^{\text{®}}$ cells. Indium and gallium growth rates were determined by monitoring intensity oscillations in the reflected high-energy electron diffraction (RHEED) patterns during the growth of GaSb and InAs under excess group-V flux. The beam equivalent pressure was equal to $1.3 \times 10^{-6}$ for Sb and $9.8 \times 10^{-7}$ for As. The substrates were initially outgassed in vacuum and the surface...
oxide was then removed at high temperature under Sb flux.

The InAs layers were grown at 0.27 ML/s with a V/III flux ratio of \(~7\). The alloy composition \(x\) in InGaSb layers was controlled by setting the Ga growth rate to 0.5 ML/s \((x=0.35)\), the corresponding V/III flux ratio was equal to 9. The temperature of \((1 \times 3)\) to \((2 \times 5)\) reconstruction transition \((T_r)\) of RHEED pattern observed on the GaSb surface was taken as a reference for all the growth temperatures. This transition temperature is the same for all the GaSb substrates under the given Sb flux. Structures presented in this article were grown at \((T_r=45)\) deg. Shutter sequences utilized for the growth of InAs/GaSb and InAs/In\(_{0.35}\)Ga\(_{0.65}\)Sb SLS are shown in Figs. 2(a) and 2(b), respectively.

B. InAs/GaSb SLS samples

To increase the operating wavelength of InAs/(In,Ga)Sb SLS detectors into LWIR region two sets of samples were grown. Set A includes five 60 period InAs/GaSb SLS samples with the same composition \((13\ \text{ML InAs/7 ML GaSb})\) and variable thickness \((0, 0.45, 0.73, 0.9,\) and \(1.35\ \text{ML})\) of InSb layer inserted between InAs and GaSb layers. Heterostructure schematic of samples in set A is shown in Fig. 3(a). Since InAs/GaSb SLS grown on GaSb substrate is under tensile strain \((\Delta a/a \sim -0.8\%)\), the purpose of InSb layer on the InAs and GaSb interface is to introduce compressive strain and then facilitate strain compensation in InAs/GaSb SLS stack. High-resolution x-ray diffraction (HRXRD) measurements performed with the Philips double-crystal x-ray diffractometer were utilized to quantify the structural properties of grown samples. Thickness of SLS period as well as lattice mismatch between zero-order SLS peak and GaSb substrate were measured for all of the samples from set A and presented in Figs. 4(a) and 4(b), respectively. It should be noted that incorporation of InSb layer in SLS stack will technically convert InAs/GaSb SLS into InAs/InSb/GaSb SLS. Within investigated range of InSb thicknesses \((0, 0.45, 0.73, 0.9,\) and \(1.35\ \text{ML})\) InSb/GaSb heterostructure presents a type-I band alignment. Thus, the InAs/InSb/GaSb heterostructure remains under type-II broken band gap alignment for all investigated thicknesses of InSb layer, with minimum conduction band in the InAs layer and maximum valence band in the thin InSb layer.

The band gap of all of the samples in set A was determined through room-temperature absorbance measurements, which were performed using a Nicolet-870 Nexus Fourier transform infrared (FTIR) spectrometer and the reflectivity module associated with it. The reflectance of the sample was calculated as a ratio of the reflected signals measured from sample and reference substrate \((n\text{-type GaSb})\). In order to eliminate the transmission component from the consideration, a thin layer of gold \((50 \text{ nm})\) was deposited on the back side of both the sample and the reference substrate. Thus, the absorbance, \(A\), as a function of wavelength is calculated using \(A=(1-R)\) relation, where \(R\) is the measured two pass reflectance of the sample. No significant changes in absorbance were observed with the variation of InSb thickness. The cutoff wavelength (defined as the wavelength where the response went to zero) for all of samples was found to be \(~8\ \mu\text{m} \) at 300 K, as illustrated in Fig. 5. The soft turn on of absorption spectrum is attributed to the thin absorption layer \((360 \text{ nm})\).

After verifying the structural and optical properties of the InAs/GaSb superlattice, a NbN infrared photodetector was grown. The concept of the NbN photodetector and its implementation in a mid-wave infrared and LWIR SLS detectors has been reported elsewhere. Absorption region of detectors with total thickness of \(~1.9\ \mu\text{m}\) consisted of 13 ML InAs/0.73 ML InSb/7 ML GaSb SLS (300 periods). The top and bottom contact layers were formed by the same SLS with Si-doped \((n=4 \times 10^{18} \text{ cm}^{-3})\) InAs layers and thicknesses of 125 and 380 nm, respectively. AlGaSb barrier with 0.2 mol fraction of aluminum was grown between top con-

![Fig. 2](Color online) Shutter sequences utilized for the growth of one period of (a) 13 ML InAs/7 ML GaSb SLS with InSb interfaces and (b) 6 ML InAs/10 ML In\(_{0.35}\)Ga\(_{0.65}\)Sb SLS with GaAs interfaces. Thickness of InSb interface varied as 0, 0.45, 0.73, 0.9, and 1.35 ML. The thickness of the GaAs layer varied from 0.5 to 2.5 ML with increment of 0.5 ML.

![Fig. 3](Heterostructure schematic of samples in sets (a) A and (b) B. In set A the thicknesses of InSb are equal to 0, 0.45, 0.73, 0.9, and 1.35 ML. In set B the thicknesses of GaSb are equal to 0, 0.5, 1.0, 1.5, 2.0, and 2.5 ML. Arrows denote the growth direction.)

![Fig. 4](a) Thickness of SLS period and (b) lattice mismatch between zero-order SLS peak and GaSb substrate measured (open circles) and calculated (solid squares) for all of the samples from set A.)
tact layer and absorbing region. In order to prevent oxidation of barrier layer during the fabrication process, thin (20 nm) GaSb layer was inserted between top contact and barrier layers. XRD (004) scan of LWIR nBn detector is shown in Fig. 6; inset to this figure represents the heterostructure schematic of the device. Normal incidence single pixel photodiodes were fabricated using standard lithography with apertures ranging from 25 to 300 μm in diameter. Details of fabrication procedure have been reported earlier.

Spectral measurements of single pixel detectors were performed using a FTIR spectrometer and a Keithley 428 preamplifier. Figure 6 shows the normalized spectral response (obtained by dividing the photocurrent of the SLS detector with that obtained using a pyroelectric detector) for a 200 μm diameter device at 77 K. Bias dependent dark currents were measured in 30–293 K temperature range. The dark current density for the same device at 77 K is shown as inset in shown in Fig. 7.

C. InAs/In\textsubscript{x}Ga\textsubscript{1-x}Sb SLS samples

Set B includes six SLS samples designed to operate at 14.5 μm with the same InAs/In\textsubscript{x}Ga\textsubscript{1-x}Sb SLS composition (6 ML InAs/10 ML In\textsubscript{0.35}Ga\textsubscript{0.65}Sb) and thickness (40 periods), and variable thickness of GaAs interface grown between InAs and In\textsubscript{0.35}Ga\textsubscript{0.65}Sb layers. Heterostructure schematic of samples in set B is shown in Fig. 3(b). The cutoff wavelength of the SLS material was calculated using pseudopotential method proposed by Dente and Tilton.46 Electronic band structure of this SLS plotted in the in-plane (II) direction with “K\textsubscript{II} =0” and growth-axis ( \perp ) direction with “K\textsubscript{I} =0” is presented in Fig. 8. The thickness of the GaAs layer was varied from 0.5 to 2.5 ML with increment of 0.5 ML. The purpose of GaAs layer was to introduce tensile strain in InAs/In\textsubscript{x}Ga\textsubscript{1-x}Sb SLS stack situated under compressive strain (Δα/α ~ 7.8%) to GaSb substrate. Within investigated range of GaAs thicknesses (0, 0.5, 1.0, 1.5, 2.0, and 2.5 ML) InGaSb/InAs heterostructure remains under type-II broken band gap alignment, with minimum valence band in the thin GaAs layer and maximum conduction band in the InGaSb layer. Structural quality of samples in set B was assessed by HRXRD measurements. Lattice mismatch of zero-

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**Fig. 5.** Absorption spectra of 13 ML InAs/7 ML GaSb SLS samples grown in set A. The cutoff wavelength was found to be ~8 μm at 300 K.

**Fig. 6.** (004) XRD scan of LWIR SLS p-i-n detector. The inset shows heterostructure schematic of the detector.

**Fig. 7.** Spectral response of LWIR detector at 77 K and 1 V of applied bias.

**Fig. 8.** Electronic band structure of 6 ML InAs/10 ML In\textsubscript{0.35}Ga\textsubscript{0.65}Sb SLS with energy gap of 14.5 μm.
order SLS peak to GaSb substrate, full width of half maximum (FWHM) of first SLS satellite peak, and SLS period thickness as a function of GaAs interface thickness are shown in Fig. 9.

III. RESULTS AND DISCUSSION

A. InAs/GaSb SLS

In set A, with the presence of the 0.73 ML thick InSb layer in each SLS period, the lattice mismatch between the first order SLS peak and GaSb substrate reaches the minimum value of 0.027% [Fig. 4(b)]. Corresponding FWHM of first SLS peak was equal to 33 arc sec. With further increased thickness of InSb interfacial layer, the SLS structure becomes compressively strained and degradation of the SLS structural quality is observed with FWHM of first SLS peak equal to 71 arc sec. We attribute this degradation to the roughening of the SLS interfaces due to, probably, change in the growth mode from layer by layer growth to three-dimensional island formation (InSb thickness exceeds 0.73 ML).47

It should be noted that strain calculation requires thickness of In–Sb interface to be 1.2 ML in order to achieve zero lattice mismatch of 13 ML InAs/7 ML GaSb SLS to GaSb substrate [Fig. 4(b), solid squares]. The discrepancy between calculated (1.2 ML) and measured (0.73 ML) thicknesses of InSb layer required to minimize strain between SLS and GaSb substrate may be explained by the presence of additional source of compressive strain in each SLS period of grown samples. One of possible sources of excessive compressive strain is the presence of thicker InSb layers in every period of SLS, and consequently, deviation of period thickness from its nominal value. However, measured thickness of SLS period closely matches its nominal calculated value, as shown in Fig. 4(a). The other possible source of excessive compressive strain is the formation of InAsSb$_{1-x}$ interfacial layers due to contamination of InSb SLS layers by back-ground Sb. In according to XRD simulations performed with BEDE scientific, the 0.6 ML of InAs$_{0.5}$Sb$_{0.5}$ in every SLS period would result in excessive strain leading to zero lattice mismatch with 0.73 ML of InSb interface thickness.

HRXRD data of LWIR nBn detector structure (Fig. 6), grown with 0.73 ML of InSb interface thickness in every period of 13 ML InAs/7 ML GaSb SLS, exhibit intense satellite peaks with a FWHM of first order SLS peak equal to 33 arc sec and a lattice mismatch of $\sim 0.03\%$, attesting to the good crystalline quality of the layers and the high reproducibility rate in the SLS period.

InAs/GaSb SLS nBn detector demonstrated the cutoff wavelength of $\sim 8.5 \mu m$ under applied bias of 1 V. It should be noted that the nBn detector structure is designed to operate under forward bias, which is defined as a negative voltage applied to the top contact of the detector. The measured dark current density at 50 mV of applied bias was as low as $3.2 \times 10^{-4}$ A/cm$^2$, which is comparable to the state-of-the-art reports for LWIR detectors based on a conventional photodiode design with suitable passivation scheme.49

B. InAs/In$_{1-x}$Ga$_x$Sb SLS

In set B, with thickness of GaAs interfacial layer equal to 2.5 ML, a zero lattice mismatch was observed, with FWHM of first SLS peak of 70 arc sec and measured period thickness of 54.3 Å (Fig. 9). The next step was to grow a thicker SLS structure for photoluminescence measurements. However, after $\sim 40$ periods of 6 ML InAs/10 ML In$_{0.35}$Ga$_{0.65}$Sb SLS growth, spotty RHEED patterns were observed indicating a 3D growth mode which implies strain relaxation in this structure.

IV. CONCLUSION

In conclusion, we investigated two approaches for extension of IR detector operating wavelength into LWIR spectral region, namely, InAs/GaSb SLS and InAs/In$_{1-x}$Ga$_x$Sb SLS material systems. By optimizing growth conditions, we grew nearly lattice matched ($\Delta a/a \approx 0.03\%$) 13 ML InAs/7 ML GaSb SLS nBn detector structure with cutoff wavelength of $\sim 8.5 \mu m$ (77 K). Dark current density was equal to $3.2 \times 10^{-4}$ A/cm$^2$ ($V_g=0.1$ V), which is comparable to the state-of-the-art reports for LWIR detectors based on a conventional photodiode design with suitable passivation scheme.

Despite certain growth challenges associated with InAs/In$_{1-x}$Ga$_x$Sb SLS, we believe that it is a promising material system for realization of LWIR devices with suppressed Auger recombination and enhanced light absorption. InAs/In$_{1-x}$Ga$_x$Sb SLSs with reduced mole fraction of In and designed to operate beyond 12 $\mu m$ are currently under investigation in our research group.

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