Midwave infrared type-II InAs/GaSb superlattice detectors with mixed interfaces

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We report the growth and fabrication of midwave infrared InAs/GaSb strain layer superlattice (SLS) detectors. Growth of alternate interfaces leads to a reduced strain between the GaSb buffer and SLS (\(\Delta \alpha/\alpha = -5 \times 10^{-4}\)), enabling the growth of active regions up to 3 \(\mu\)m (625 periods). The structural, optical, and electrical properties of the active region were characterized using x-ray crystallography and photoluminescence, respectively. \(p-i-n\) detectors were grown using 625 periods of 8 ML (monolayer) InAs/8 ML GaSb as the active region. The \(\lambda_{\text{cutoff}}\) for the detectors was 4.6 \(\mu\)m with a conversion efficiency of 32\% at \(V_b = -0.2\) V. Detectivity was obtained using noise power spectral density measurements under 300 K 2\(\pi\) field of view illumination and was equal to \(5.2 \times 10^{10}\) and \(3 \times 10^{10}\) cmHz\(^{1/2}\)/W (\(V_b = -0.02\) V, \(T = 80\) K) in the white noise and 1/f noise limit (at 50 Hz).

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I. INTRODUCTION

Midinfrared detectors based on InAs/(In,Ga)Sb strain layer superlattices (SLSs) have been investigated for the past 15 years, ever since they were proposed by Smith and Malhiot.\(^1\) The main advantage of this system lies in the fact that the band gap of the superlattice can be tailored over a wide range (2 \(\mu\)m < \(\lambda < 30\) \(\mu\)m) by varying the thickness of the constituent materials. Thus using two “mid-” band gap semiconductors, devices can be fabricated with an operating wavelength spanning the entire midwave infrared (MWIR) regime, like character or a GaAs-like character. Since the lattice constant of InSb (GaAs) is much larger (smaller) than that of the GaSb substrate, a few monolayers of these materials leads to a large compressive (tensile) strain, thereby dramatically altering the structural, optical and electrical properties of the SLS. We believe that to produce a high quality SLS material, the nature of the interfaces must be controlled accurately by monitoring the growth temperature, group III/V flux ratio and the group V soak times. In this paper, we report a high performance InAs/GaSb detector grown with alternate interfaces with a cutoff wavelength of 4.6 \(\mu\)m, with a conversion efficiency of 32\% at \(V_b = -0.2\) V, 80 K, a white noise limited \(D^* = 5.2 \times 10^{10}\) cmHz\(^{1/2}\)/W, 1/f-noise \(D^* = 3 \times 10^{10}\) cmHz\(^{1/2}\)/W at 50 Hz [\(V_b = -0.02\) V, \(T = 80\) K, and 300 K 2\(\pi\) field of view (FOV) illumination] and observable spectral response near room temperature. It must be noted that the \(D^*\) measured with a 300 K background is the most realistic condition for a detector under field test conditions (unlike the zero FOV \(D^*\) reported by some groups).

II. GROWTH AND CHARACTERIZATION

The structures were grown in a solid source VG-80 molecular beam epitaxy (MBE) reactor on undoped epiready (100) GaSb substrates using As\(_2\) and Sb\(_2\) sources. Group-III fluxes were calibrated by monitoring intensity oscillations in the reflected high-energy electron diffraction (RHEED) patterns, while group-V fluxes were adjusted using a conventional ion gauge to satisfy group V/III beam equivalent pressure ratio equal to ~3.5. Prior to the growth of the detectors, two sets of calibration samples with 8 ML (molecular) InAs/8 ML GaSb and 8 ML InAs/24 ML GaSb were grown on GaSb substrates. Symmetric (004) and asymmetric (224) x-ray scans were performed on the samples with a Philips double-crystal X-ray diffractometer using the Cu \(K\alpha_1\) line. From the spacing between the satellite fringes, the exact growth rates and thicknesses of the InAs and GaSb layers were determined.\(^10\)

For the purpose of optimization of the strain in the structure, samples with different As/Sb soak times were grown. Set A includes six samples with 20 periods of 8 ML InAs/8 ML GaSb SLS grown with fixed As-soak time (4 s) and variable Sb-soak times. Set B includes three samples with 100 periods of 8 ML InAs/8 ML GaSb grown with fixed...
plane lattice mismatch
SLS. Full width at half maximum rates were equal 0.5 ML/s for both constituent layers of the both sets and presented in the Figs. 1 order peak of SLS and GaSb substrate were calculated for order peak of SLS as well as lattice mismatch between zero-

sible

with alternate interfaces tion edge.
The superlattices were grown using optimized design with alternate interfaces \( a \approx 1 \text{ ML} \) thick which yields an inplane lattice mismatch \( \Delta a_0/a = -5 \times 10^{-4} \). Figure 2(a) shows the symmetrical (004) scan of a 625 period InAs 8 ML/GaSb 8 ML sample.

The band gap of the superlattice was determined through photoluminescence (PL) measurements, which were performed using a Nicolet-870 Nexus Fourier transform infrared (FTIR) spectrometer and SR830 DSP lock-in amplifier. The PL sample consisted of 100 periods of 8 ML InAs/8 ML GaSb SLS whereas the sample used for the x-ray analysis was an actual detector structure with 625 periods of 8 ML InAs/8 ML GaSb SLS. A 200 Å AlSb barrier was grown below the SLS to capture the photoexcited carriers. PL measurements were performed at 77 K with 980 nm laser with excitation fluence of 0.5 W. Figure 2(b) shows a photoluminescence spectrum from the sample. The band gap obtained from the PL measurements is in very good agreement with the theoretical prediction of the pseudopotential model proposed by Dente and Tilton.\(^1\) This theoretically predicted value is depicted by the arrow in Fig. 2(b).

After verifying the structural and optical properties of the superlattice, \( n-i-p \) detectors were grown. The active region consisted of 625 periods of 8 ML InAs/8 ML GaSb SLS. The bottom GaSb Be-doped buffer layer \( (p = 2 \times 10^{17} \text{ cm}^{-3}) \) 0.5 \( \mu \text{m} \) thick was grown at \( \sim 525 ^\circ \text{C} \) whereas the nominally undoped SLS active region and the InAs Te-doped contact layer \( (n = 5 \times 10^{16} \text{ cm}^{-3}) \) were grown at \( \sim 475 ^\circ \text{C} \). Normal incidence single pixel photodiodes were fabricated using standard lithography with apertures ranging from 25–300 \( \mu \text{m} \) in diameter. For the \( n \)-type contact, Ti (500 Å)/Au(300 Å) was used followed by an isolation
etch. P-contact metal Ti (500 Å)/Pt (500 Å)/Au (2000 Å) was deposited on the back of the substrate. Devices were then wire bonded to a leadless chip carrier for further characterization.

III. RESULTS AND DISCUSSION

Spectral measurements were performed using a FTIR spectrometer and a Keithley 428 preamplifier. Figure 3 shows normalized spectral response (obtained by dividing the photocurrent of the SLS detector with that obtained using a pyroelectric detector) for a 300 μm diameter device for different temperatures at the same bias. The spectral response from the SLS detector was visible at room temperature. This suggests the potential of the SLS technology for realizing high operating temperature (HOT) sensors.

Current-voltage curve was obtained using a semiconductor parameter analyzer and is shown in Fig. 4(a). To obtain an estimate for the conversion efficiency (the product of the quantum efficiency and the gain) of the diode, the background photon irradiance ($E_q$, photons s⁻¹ cm⁻²) on the detector was calculated using

$$E_q = \frac{\pi L_q}{4(F\#)^2} = \pi L_q \sin^2(\theta_{max}/2),$$

where $L_q$ is the total spectral radiance from a 300 K source (1.3 x 10¹⁸ photons s⁻¹ cm⁻² sr⁻¹), $\theta_{max}$ is the FOV, and F# is the f number of the limiting aperture. In our setup, the diodes were illuminated by a 300 K scene with a 2 π FOV. Using this geometry, the background irradiance on the detector was found to be 3.4 x 10¹⁷ photons s⁻¹ cm⁻² and the conversion efficiency was estimated using the following equation

$$\eta = \frac{I_p}{\int W(\lambda,T)R'_{ad}(\lambda)d\lambda}A_d\sigma \epsilon \pi,$$

where $I_p$ is the measured photocurrent, $W(\lambda,T)$ is the photon incidence, $R'_{ad}(\lambda)$ is the relative responsivity, and $A_d$ is the effective optical area of the diode. To account for scattering in the substrate, the effective optical area was assumed equal to the area of the entire chip. The calculated value of the conversion efficiency is shown in Fig. 4(b). These values are in a good agreement with values obtained by other research groups. Responsivity measurements were also undertaken using a calibrated black body source, 400 Hz optical chopper, SR 770 FFT Network signal analyzer and Keithley 428 preamplifier. (Figure 5).

To obtain the detectivity, a very careful noise analysis and measurement was undertaken. In the literature, the most commonly reported values for the $D^*$ are the Johnson noise limited $D^*$ (obtained from the $R_pA$ product) sometimes undertaken under a zero FOV condition. However, this is not a good measure of the detector performance for the system designer since the detector in any imaging system will be observing a 300 K background. To obtain the true detector

FIG. 3. The normalized spectral response ($\lambda_{cutoff}=4.6$ μm) from a 300 μm diameter device (calculated by dividing the photocurrent of the SLS detector with that obtained from a pyroelectric detector) for different temperatures.

FIG. 4. (a) Current-voltage relationship of the p-i-n diode under a 2 π field of view (FOV) from a 300 K scene. (b) Calculated value of the conversion efficiency at $V_b=-0.2$ V.

FIG. 5. Noise current spectrum obtained at $V_b=-0.02$ V, $T=80$ K. The white noise limited $D^*$ and the 1/f noise limited $D^*$ are shown in the figure. Background system noise is also shown.
limited $D^*$, one must obtain all the sources of noise and then determine the various noise limiting mechanisms. In our case, this was done by measuring the noise power spectral density (PSD) with the detector seeing a 300 K scene with a 2$\pi$ FOV. This is the most realistic operating condition for a detector under field test conditions. In order to have a better frequency resolution the entire frequency range (1 Hz–100 kHz) was divided into several parts each containing two to three frequency decades and then the different subranges were superimposed to obtain the final range. For each small subrange spikes were ignored as artefacts of measurements. Figure 4 shows the noise spectrum, i.e., noise current as a function of frequency along with the background system noise. From this figure, the $D^*$ under different noise limiting mechanisms (1/f noise, white noise etc) can be obtained.

For example, to obtain the white noise limited $D^*$ (including shot noise and Johnson noise) we used the following equation,

$$D^* = \frac{R\sqrt{A\Delta f}}{I_{\text{white}}},$$

where $R$ is the measured responsivity, $A$ is the electrical area of diode, and $I_{\text{white}}$ is the white noise current (obtained by integrating the noise spectrum in a bandwidth of $\Delta f$ beyond the corner frequency). From the white noise portion of the spectrum, we obtained $D^* = 5.2 \times 10^{10}$ cm Hz$^{1/2}$/W (V = −0.02 V at 80 K, 300 K scene with 2$\pi$ FOV). Similarly, the 1/f noise limited $D^*$ at 50 Hz is equal to $3 \times 10^{10}$ cm Hz$^{1/2}$/W under the same operating conditions. Room temperature measurement on similar devices yielded a Johnson noise limited $D^*$ equal to $4.6 \times 10^9$ cm Hz$^{1/2}$/W for $V_b = −0.3$ V at room temperature.

IV. CONCLUSIONS

In conclusion, we report midinfrared InAs/GaSb SLS detectors ($\lambda_{\text{cutoff}} = 4.6$ $\mu$m) grown by molecular beam epitaxy operating near room temperature. The conversion efficiency was estimated to 32% at $V_b = −0.2$ V, using background illumination from a 300 K scene. We believe that the improved conversion efficiency is due to the optimized growth conditions including the optimization of As- and Sb-soak times. The detectivity $D^*$ was estimated by measuring the noise spectrum at 80 K and the white noise and 1/f noise limited $D^* = 5.2 \times 10^{10}$ and $3 \times 10^{10}$ cm Hz$^{1/2}$/W, respectively.

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