ELSEVIER

Microelectronics Journal 36 (2005) 256–259

Microelectronics Journal

www.elsevier.com/locate/mejo

Design of InAs/Ga(In)Sb superlattices for infrared sensing

G.J. Brown*, F. Szmulowicz, H. Haugan, K. Mahalingam, S. Houston

Air Force Research Laboratory, Materials and Manufacturing Directorate, AFRL/MLPS, 3005 Hobson Way, Wright Patterson AFB, OH 45433-7707, USA

Available online 12 April 2005

Abstract

New infrared detector materials with high sensitivity, multi-spectral capability, improved uniformity and lower manufacturing costs are required for numerous infrared sensing applications. One material system has shown great theoretical and experimental promise for these applications: $InAs/In_xGa_{1-x}Sb$ type-II superlattices. These superlattices offer a large design space for adjusting not only the energy band gap of the material but also the band structure. The infrared properties of several sets of designs of InAs/GaSb superlattices were studied. These designs covered the mid-infrared spectral band from 3 to 6 μm. Optimization design rules were explored. The infrared photoresponse spectra, combined with 8×8 $\mathbf{k}\cdot\mathbf{p}$ envelope function approximation modeling of superlattice band gaps and absorption spectra, provide insight into the underlying physics behind the optimized design of these materials.

Keywords: Superlattice; InAs/GaSb; Infrared; Detectors

1. Introduction

$InAs/In_xGa_{1-x}Sb$ superlattices (SLs) are the III–V equivalent to the well established $Hg_xCd_{1-x}Te$ alloys used for infrared detection in the short, mid and long wavelength bands of the infrared spectrum [1–3]. Similar to HgCdTe, the InAs/Ga(In)Sb superlattices can be designed with a wide range of energy band gaps which enables covering wavelength bands from 3 to 30 μm. Unlike the HgCdTe alloys these superlattices offer the ability to tailor the energy band structure as well as the band gap. And because there are many different superlattice designs that can create the same band gap, the band structure changes are a key consideration in selecting an optimized design. Other design factors are maintaining a lattice match to the growth substrate, typically GaSb, and keeping the individual layers of InAs and GaSb to a reasonable thickness, compatible with growth by molecular beam epitaxy (MBE).

For this study, a several series of samples were grown to explore the parameter space for superlattices covering one of the key infrared imaging windows of 3–5 μm. For the relatively large band gaps needed to cover this wavelength range, 400–200 meV, very thin InAs and GaSb layers are used. Indium doping of the GaSb is not required to reduce the thickness of each layer to enhance electron and hole wave function overlap, and hence optical absorption, as is typically done for long wavelength designs. So, for these mid-infrared superlattices, the design parameters involve choices of GaSb and InAs layer thickness, plus composition and thickness of the interfacial layers. These relatively few and simple parameters still leave a fair amount of design space to be explored. For instance, using quantum mechanical modeling, at least 20 different layer combinations could be used to create band gaps close to 300 meV. From these combinations, a smaller set of designs could be selected based on reasonable layer thickness, i.e. greater than 1 or 2 monolayers or larger optical oscillator strength. However, it was decided to explore as much of the parameter space experimentally to verify the accuracy of the modeling of the optical absorption and band gaps due to some unique behavior that occurs in these very thin superlattice periods (<60 Å).

* Corresponding author. Tel.: +1 937 255 4474; fax: +1 937 255 4913.
E-mail address: gail.brown@wpafb.af.mil (G.J. Brown).

0026-2692/$ - see front matter © 2005 Published by Elsevier Ltd.
doi:10.1016/j.mejo.2005.02.020

2. MBE growth

The InAs/GaSb superlattices were grown by molecular beam epitaxy (MBE) using standard gallium and indium sources, and valved cracker cells for the antimony and arsenic sources. The superlattices were grown on (100) GaSb substrates with a 0.5 μm GaSb buffer layer.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **12 APR 2005**	2. REPORT TYPE	3. DATES COVERED **00-00-2005 to 00-00-2005**

4. TITLE AND SUBTITLE **Design of InAs/Ga(In)Sb superlattices for infrared sensing**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air Force Research Laboratory, Materials and Manufacturing Directorate,AFRL/MLPS, 3005 Hobson Way,Wright Patterson AFB,OH,45433-7707**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

The growth temperature was 410±5 °C and the V/III beam equivalent pressure flux ratio was approximately 3.5 for the InAs and 2.5 for the GaSb growths. Slow growth rates were used for precision epitaxy through which layer thicknesses were controlled to within half of a monolayer (1.5 Å). The accuracy of the intended SL designs were checked post-growth by X-ray diffraction (XRD) and cross-sectional transmission electron microscopy (XTEM). The periods measured by XRD were close to the intended periods to within the experimental error of 0.7 Å, and residual strains in the SL layers were negligible. XTEM was used as second check on SL period as well determining the individual layer thicknesses. For example, the average values for the individual layer thicknesses of InAs (21.4±2.6 Å) and GaSb (27.8±2.5 Å) as measured from XTEM image closely matched the respective intended values of 20.5 and 27.0 Å. MBE growth conditions were selected to minimize surface defects and interface roughness.

3. Experiment

Spectral photoconductivity was measured using a BIO-RAD FTS-6000 Fourier transform infrared spectrometer. The SL samples were cut into 3 mm×5 mm rectangles and indium strip contacts were applied down the long sides on the top surface. The samples were mounted on the coldfinger of a close-cycle refrigerator with a cooling range from 10 to 290 K. For data collection, the samples were biased with a constant current of 0.15 mA and a current sensitive preamplifier was used. The measured spectra were background corrected using a reference spectrum.

4. Results

Our previous studies of InAs/GaSb sample designs for infrared detection in the 3–5 μm atmospheric window found that for an InAs thickness of 20.5 Å the maximum photoresponse was obtained with a GaSb thickness of 27 Å [4]. In that study the GaSb widths explored had ranged from 18 to 27 Å in 3 Å increments. However, the photoresponse spectrum only covered part of the desired 3–5 μm range since the cut-off wavelength (λ_c), at 50% of the signal strength, was 4.03 μm at 10 K. For this study, we grew two new sample sets. The first set had InAs width of 26 Å, to narrow the SL band gap, and GaSb layer widths ranging from 15 to 27 Å. The normalized photoresponse spectra measured for this series of samples is shown in Fig. 1. In this set the band gap shifted from 177.5 to 227 meV as the GaSb layer width was increased from 15 to 27 Å. The corresponding cut-off wavelengths range from 6.47 to 5.24 μm. This sample set overshoots the 3–5 μm window.

The second sample set had a fixed GaSb width of 27 Å and InAs layer widths ranging from 13 to 26 Å.

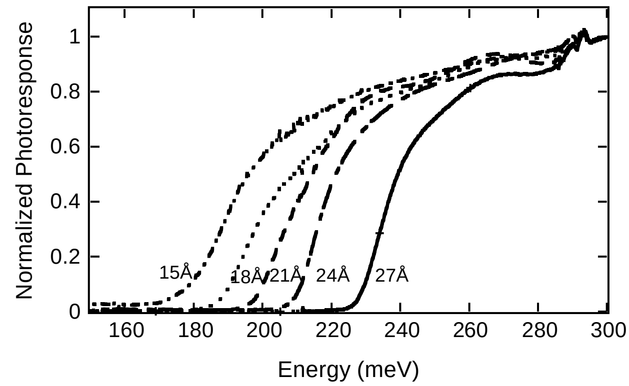

Fig. 1. Composite of photoresponse spectra for 5 superlattice samples with a fixed InAs width of 26 Å and varied GaSb widths from 15 to 27 Å. Spectra were collected at $T=10$ K.

The normalized photoresponse spectra measured for this series of samples is shown in Fig. 2. In this set the band gap shifted from 402 to 235 meV as the GaSb layer width was increased from 13 to 26 Å. The corresponding cut-off wavelengths range from 3.02 to 5.08 μm. This sample set nicely spans the 3–5 μm window, with the 26 Å InAs width providing coverage of the whole infrared window.

There was one sample in each series with an InAs width of 26 Å and a GaSb width of 27 Å. These samples did not have exactly the same cut-off wavelength or band gap, 227 versus 235 meV. The reason is that these two samples were grown with slightly different interfaces. The interfaces were controlled to InSb-like in both cases but for the fixed InAs width series the growth time of the interfaces was twice as long as for the series with fixed GaSb width. The difference in the XRD measured periods of the two samples was only 56.5 versus 55.8 Å. This demonstrates how the selected interface composition and width can be used as an additional parameter to adjust the SL optical properties.

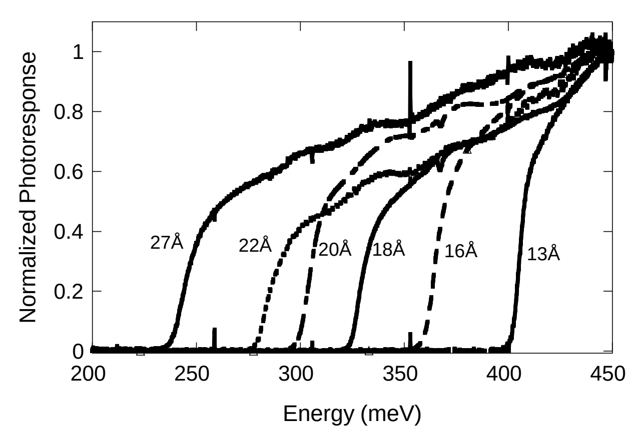

Fig. 2. Composite of photoresponse spectra for six superlattice samples with a fixed GaSb width of 27 Å and varied InAs widths from 13 to 27 Å. Spectra were collected at $T=10$ K.

5. Discussion

In addition to looking at the spectral range of the various samples, the magnitude of the sample photoresponse was also considered. While the FTIR photoresponse measurements are not quantitative in the sense of being to assign units like amps per watt, samples run sequentially under the same run conditions, such as infrared beam intensity, temperature and bias current, can be compared relative to one another. It is rather surprising how much the signal strength can systematically vary between the different sample designs. A composite of the six spectra collected from the samples in the fixed GaSb width series is shown in Fig. 3. The designs on either side of 16–20 Å show a marked decrease in the measured photoconductive signal.

Modeling predicts that the absorption coefficient of these designs will vary slightly, with the oscillator strength increasing for decreasing SL period. However, the observed variation in the photoresponse intensity is larger than the calculated changes in oscillator strength, and the smallest period superlattice had one of the weakest signals. Similar variations were observed in other systematic sample sets grown only days apart. Further analysis is needed to explain the underlying factors in the observed optimized designs.

The energy band structure and absorption coefficient spectra were calculated for the SL designs by a modified 8×8 envelope function approximation [5]. The standard EFA was modified to include the effect of in-plane asymmetry at InAs/GaSb interfaces. This model was successful at calculating energy band gaps of a variety of InAs/GaSb SL designs reported in the literature, as well as measured by us. An example of the good agreement between calculated and measured band gaps for the same SL design is shown in Fig. 4. Despite the good agreement on the energy for the start of the above band gap optical transitions, at about 250 meV, the overall shape of the calculated and measured spectra are quite different. This was not the case for SL designs with much smaller band gaps, where good agreement between calculated and measured spectra was observed [6]. Additional improvements to our EFA model are planned.

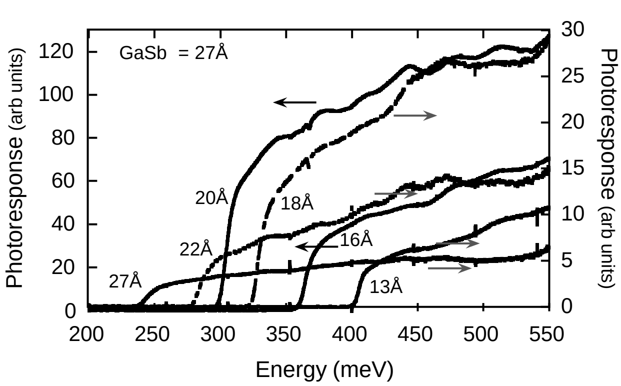

Fig. 3. Six intensity versus photon energy photoresponse spectra at $T=10$ K. The GaSb width in all the SLs was 27 Å, the InAs widths were varied as indicated on the graph. Arrows indicate which y-axis applies to each of the spectra.

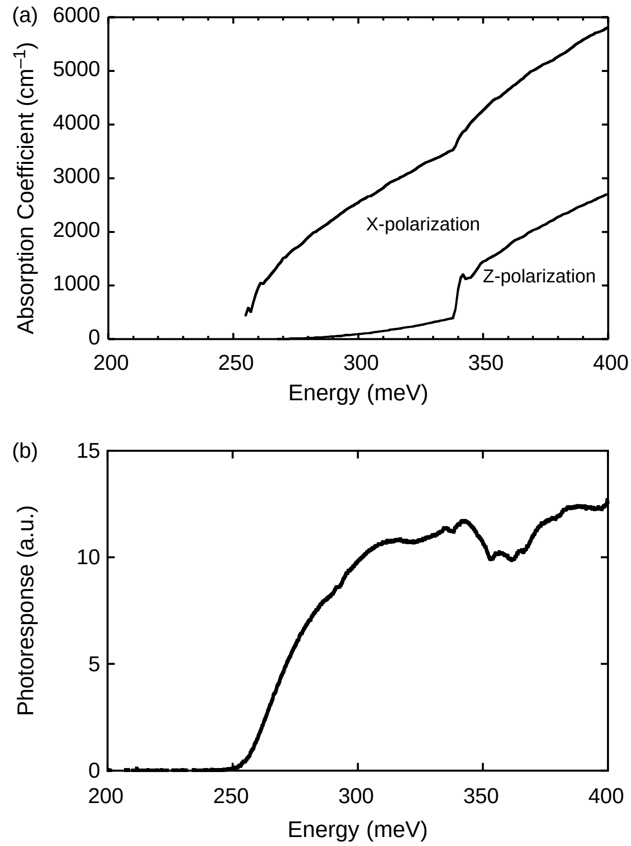

Fig. 4. Comparison of calculated absorption coefficient spectra (a) and measured photoresponse spectrum (b) for a superlattice with InAs = 20.5 Å and GaSb = 18 Å. Infrared light at normal incidence to the sample surface is x-polarized.

6. Conclusions

For thin GaSb layer widths, <30 Å, the observed trend in band gap shift with decreased GaSb layer width is opposite to what occurs for decreasing InAs layer widths. This trend is consistent with data reported for a similar sample set and occurs due to increased electron wave function overlap in the InAs layers as the separating GaSb layer is decreased [4]. Two sets of systematic SL designs were explored where one of the layer thickness parameters was fixed while the other was varied in one monolayer increments. The design that had the maximum photoconductive signal was for a superlattice with an InAs width of 20 Å and a GaSb width of 27 Å. Further SL growths will focus on adjusting the GaSb to widths >27 Å and using InAs widths near 20 Å to push the cut-off wavelength closer to 5 μm. Additional work on the modeling of the InAs/GaSb SL physics is planned to understand the sharp differences between the calculated absorption spectra and the measured photoresponse spectra.

Acknowledgements

This work was supported by the Air Force Office of Scientific Research (AFOSR/NE) through Lt. Col. Todd Steiner.

References

[1] Y. Wei, M. Razeghi, High quality type-II InAs/GaSb superlattices with cut-off wavelength ∼3.7 μm using interface engineering, Journal of Applied Physics 94 (2003) 4720–4722.

[2] F. Fuchs, L.O. Burkle, R. Hamid, N. Herres, W. Pletschen, R.E. Sah, R. Kiefer, J. Schmitz, Optoelectronic properties of photodiodes for the mid- and far-infrared based on the InAs/GaSb/AlSb materials family, SPIE Proceedings on Photodetectors: Materials and Devices VI 4288 (2001) 171–182.

[3] H. Mohseni, M. Razeghi, G.J. Brown, Y.S. Park, High-performance InAs/GaSb superlattice photodiodes for the very long wavelength range, Applied Physics Letters 78 (2001) 2107–2109.

[4] H.J. Haugan, F. Szmulowicz, G.J. Brown, K. Mahalingam, Optimization of mid-infrared InAs/GaSb type-II superlattices, Applied Physics Letters 84 (2004) 5410–5412.

[5] F. Szmulowicz, H. Haugan, G.J. Brown, Effects of interfaces and the spin-orbit band on the band gaps of InAs/GaSb superlattices beyond the standard envelope-function approximation, Physical Review B 69 (2004) 1553211–1553217.

[6] G.J. Brown, F. Szmulowicz, InAs/InGaSb superlattices for very long wavelength infrared detection, SPIE Proceedings on Photodetectors: Materials and Devices VI 4288 (2001) 200–208.