COMPARISON OF IDEAL InAs/InAs$_{1-x}$Sb$_x$ and InAs/In$_x$Ga$_{1-x}$Sb SUPERLATTICE IR DETECTORS

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The theoretical performance limits of 10μm 70.7ÅInAs/21ÅIn$_{0.61}$Sb$_{0.39}$ and 11μm 39.8ÅInAs/15ÅIn$_{0.7}$Ga$_{0.3}$Sb superlattice-based IR detectors are compared. Detailed calculations of electronic band structures, radiative and Auger recombination rates, and detectivities are reported. Both systems promise superior performance to conventional technology based on HgCdTe, primarily due to suppressed band-to-band Auger recombination rates. The predicted optical absorption and detectivities of the InAs/InAs$_{1-x}$Sb$_x$ system are within a factor of two of those of the InAs/In$_x$Ga$_{1-x}$Sb superlattice over the 77K-200K range, while both have detectivities more than a factor of three greater than HgCdTe.

Introduction

The development of superlattice-based IR detectors is motivated by the promise of performance advantages over conventional technology based on bulk HgCdTe. Recent interest in InAs/InAs$_{1-x}$Sb$_x$ superlattices (SLs) for multi-spectral IR detection and emission prompts our evaluation of theoretical performance limits for ideal (defect-free) structures. Indications that defect levels in InAs-rich alloys lie in the conduction band rather than in the fundamental gap motivate the study of this superlattice[1, 2]. Although such superlattices are frequently grown on highly mismatched substrates such as GaAs[3], in this work we consider InAs/In$_{0.61}$Sb$_{0.39}$ superlattices grown on GaSb substrates, with layer widths chosen to balance the strain within a superlattice layer.

A similar system, InAs/In$_x$Ga$_{1-x}$Sb, has received extensive experimental[4] and theoretical[5, 6] attention. Ideal InAs/In$_x$Ga$_{1-x}$Sb detectors have greater detectivities than ideal HgCdTe detectors due to the suppression of Auger recombination[7, 8] and the reduction of tunneling currents. Carrier lifetimes up to two orders of magnitude longer than those of HgCdTe have been observed[9], and detectivities comparable to those of HgCdTe have been achieved in the long-wavelength infrared (LWIR) spectral range[10]. A comparison between InAs/InAs$_{1-x}$Sb$_x$ and InAs/In$_x$Ga$_{1-x}$Sb will help elucidate the potential of the former system.
Several similarities are apparent between these two systems. Since InAs and GaSb have almost the same lattice constant, the alloys In$_x$Ga$_{1-x}$Sb and InAs$_{1-x}$Sb$_x$ have roughly the same lattice constant for a given $x$. Similar deformation potentials and elastic constants imply these alloys will have similar heavy-light hole splittings. The band offset for intermediate alloy compositions is type II for both systems. For InAs/InAs$_{1-x}$Sb$_x$, experimental measurements[3, 11, 12] and theoretical calculations[13, 14] indicate the offset is type II for all but small values of $x$[15]. For intermediate values of $x$ the band offsets are also comparable: for InAs$_{0.81}$Sb$_{0.19}$ the offset $\Lambda = 0.351$eV[12], while for In$_{0.4}$Ga$_{0.6}$Sb the band offset is 560meV[16]. A qualitative difference in the band structures comes from the alloy band gap. Unstrained InAs$_{0.61}$Sb$_{0.39}$ has a smaller band gap than InAs (0.218eV versus 0.418eV) whereas unstrained In$_{0.4}$Ga$_{0.6}$Sb’s band gap is larger (0.483eV).

Methods and Results

The calculations were performed utilizing non-parabolic electronic band structures and momentum-dependent matrix elements calculated with a SL crystal K-p formalism[17, 18] using the parameters in Table I for InAs/InAsSb and those in Ref.[8] for InAs/InGaSb. The bands are found to be highly non-parabolic, and the momentum matrix elements show strong dispersion. The effective mass approximation, therefore, is not applicable. The bands of 10µm 70.7ÅInAs/21ÅInAs$_{0.61}$Sb$_{0.39}$ are calculated for pseudomorphic growth on GaSb substrates and a type-II band alignment with a valence band offset of 0.351eV[12]. The alloy band gap is chosen as 0.218eV[19], close to other values of 0.183eV[20] and 0.192eV[21]. The alloy composition corresponds to the minimum gap for two of these parametrizations.

Figure 1 shows the calculated band structure of 10µm 70.7ÅInAs/21ÅInAs$_{0.61}$Sb$_{0.39}$ grown on GaSb. Biaxial compression breaks the degeneracy of the heavy hole and light hole edges, shifting the heavy hole up and the light hole down. The corresponding SL heavy and light hole bands are therefore split. When this splitting exceeds the energy gap, the Auger recombination of the carriers is suppressed in p-type materials[22]. Strain in InAs/In$_x$Ga$_{1-x}$Sb SLs produces similar effects. The heavy-light hole splitting in the 70.7Å InAs/ 21Å InAs$_{0.61}$Sb$_{0.39}$ SL (0.20eV) is not as great as that of 39.8ÅInAs/15ÅIn$_{0.4}$Ga$_{0.6}$Sb (0.24eV) due to slightly lesser strain. Since these splittings both substantially exceed the fundamental gap, the difference in Auger recombination rates is minor. The band structure of the InAs/InGaSb superlattice is shown in Ref.[8]. The heavy-hole mass in the InAs/InAsSb superlattice is heavier than in the InAs/InGaSb superlattice, enhancing Auger rates in the former.

Plotted in figure 2 is the calculated optical absorption spectrum of 70.7ÅInAs/ 21ÅInAs$_{0.61}$Sb$_{0.39}$ compared with that of 39.8ÅInAs/15ÅIn$_{0.4}$Ga$_{0.6}$Sb and bulk HgCdTe. Since the electrons are spread out over both SL layers, while the heavy holes are confined to the alloy regions, the wider InAs layers in the InAs/InAs$_{1-x}$Sb$_x$ superlattice produce smaller optical matrix elements between these bands than in the InAs/In$_x$Ga$_{1-x}$Sb superlattice. Weaker dipole matrix elements result in lower absorption in the former system. Nevertheless, an absorption coefficient of 1500 cm$^{-1}$ is substantial enough to warrant further examination of the InAs/InAs$_{1-x}$Sb$_x$ system.
for IR detection applications. The absorption coefficients of 1500 cm\(^{-1}\) and 2000 cm\(^{-1}\) were employed in the evaluation of the detectivities of the InAs/InAsSb and InAs/InGaSb systems, respectively.

Nonparabolic bands and momentum-dependent matrix elements were employed for the calculation of Auger and radiative recombination lifetimes\([22]\). We find that AM-7 transitions are the dominant band-to-band recombination transitions involving hole-hole collisions in these superlattices. These AM-7 transitions involve two holes in the heavy hole band, an electron in the lowest conduction band, and an electron in the light hole band\([23]\).

Figure 3 shows calculated values of the detectivity \(D^*\) for the two LWIR SLs. These theoretical maximum values of \(D^*\) were obtained from the expressions \(D^* = (\eta/2h\nu)(\tau_n/\tau_p L_n)^{1/2}\) for n-on-p photodiodes\([24]\). Here \(\eta\) is the quantum efficiency given by \(L_{\{n\}}\alpha/(L_{\{n\}}\alpha + 1)\)\([25]\). The minority carrier lifetime in the p-type layers is \(\tau_n\). The minority carrier diffusion length, \(L_n\), is proportional to \(\tau_n^{1/2}\) so that \(D^*\) is proportional to \(\tau_n^{1/4}\). Calculated detectivities are theoretical upper bounds due to the neglect of other recombination mechanisms such as Shockley-Read-Hall. In both systems, we consider an acceptor density of \(10^{17}\) cm\(^{-3}\) in the p-type layers (which is optimum for the InAs/InGaSb superlattice) and a vertical electron mobility of 1000 cm\(^2\)/V-s. In this doping range the SL \(D^*\) is over an order of magnitude greater than bulk HgCdTe. All other parameters are defined and given in refs. \([7]\) and \([24]\). Further details concerning the evaluation of the detectivity may be found in Ref. \([8]\).

Due to suppression of Auger recombination pathways in both SLs, \(\tau_n\) is dominated by radiative recombination below about 100K in both systems. The larger gap of 70.7\(\text{Å}\)InAs/21\(\text{Å}\)InAs\(_{0.61}\)Sb\(_{0.39}\) results in lower minority carrier concentrations, hence somewhat higher detectivities than 39.8\(\text{Å}\)InAs/15\(\text{Å}\)In\(_{0.4}\)Ga\(_{0.6}\)Sb below 100K. The greater suppression of hole-hole Auger recombination in 39.8\(\text{Å}\)InAs/15\(\text{Å}\)In\(_{0.4}\)Ga\(_{0.6}\)Sb due to its greater heavy-light hole band splitting results in greater detectivities for this system at higher temperatures. In comparison, the minority carrier lifetimes of bulk Hg\(_x\)Cd\(_{1-x}\)Te are dominated by Auger recombination over the plotted temperature range\([22]\). Hence, both LWIR SLs are predicted to have greater detectivities than bulk Hg\(_x\)Cd\(_{1-x}\)Te.

11 \(\mu\text{m}\) HgCdTe detectivities are predicted to be lower than the upper bounds predicted for the optimum 11 \(\mu\text{m}\) InAs/InGaSb SL due to the heavy doping of the SL reducing the minority carrier density and hence the noise current. The minority carrier lifetimes are not as short as they would be in HgCdTe with the same doping due to the suppression of band-to-band Auger recombination in the SL. The greater detectivities of the SL lead to substantial improvements in background limited operating temperatures. The SL's are further benefited by their compatibility with III-V electronics, good material strength, and insensitivity to alloy potential fluctuations.

We conclude that the IR detector performance of InAs/In\(_x\)Ga\(_{1-x}\)Sb SLs slightly exceed that of InAs/InAs\(_{1-x}\)Sb\(_x\) SLs. Both offer potential improvements in \(D^*\) of over a factor of three relative to optimally-doped bulk Hg\(_x\)Cd\(_{1-x}\)Te at 11 \(\mu\text{m}\). The high predicted detectivities for InAs/InAs\(_{1-x}\)Sb\(_x\) SLs with gaps in the LWIR suggest that they are promising for IR detector applications. The performance difference between InAs/InAs\(_{1-x}\)Sb\(_x\) and InAs/In\(_x\)Ga\(_{1-x}\)Sb systems is small enough that the practical distinction will likely always originate from growth-related differences — such as
possible ineffectiveness of the Shockley-Read-Hall mechanism in the InAs/InAs$_{1-x}$Sb$_x$
superlattices.

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References

[10] R.H. Miles, private communication


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<th>Parameter</th>
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Notes: All values are at $T=0K$. Hydrostatic deformation potentials of the valence bands are neglected. All parameters for InAs$_{0.61}$Sb$_{0.39}$ are linearly interpolated from InAs and InSb unless otherwise noted in the InAs$_{0.61}$Sb$_{0.39}$ column. The superlattice is assumed to be grown on a GaSb substrate.

3 Momentum matrix element deduced from $m^*_e$ of InAs and InSb.
4 Y. Zhang, private communication.
5 Same value as InAs/In$_x$Ga$_{1-x}$Sb.
Figure 1 Calculated band structure of 10μm 70.7ÅInAs/21ÅInAs<sub>0.61</sub>Sb<sub>0.39</sub>. Bands are plotted in the in-plane (||) and growth-axis (⊥) directions.

Figure 2 The optical absorption coefficients calculated employing $k \cdot p$ theory for 10μm 70.7ÅInAs/21ÅInAs<sub>0.61</sub>Sb<sub>0.39</sub>, 11μm 39.8ÅInAs/15ÅInGaSb, 70.7ÅInAs/21ÅInAsSb and 11μm bulk HgCdTe.
Figure 3 Predicted specific detectivities for IR detectors with ideal 10µm 70.7Å InAs/21Å InAs$_{0.61}$Sb$_{0.39}$, 11µm 39.8Å InAs/15Å In$_{0.4}$Ga$_{0.6}$Sb, and 11µm bulk HgCdTe active layers. The n-on-p SL p-type layers have an acceptor concentration of $10^{17}$ cm$^{-3}$. The p-on-n HgCdTe n-type layer has a donor concentration of $10^{15}$ cm$^{-3}$. 