INFRARED DETECTIVITIES OF 11 TO 17 \( \mu \text{m} \) IDEAL InAs/In\(_x\)Ga\(_{1-x}\)Sb SUPERLATTICES

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The performance characteristics of InAs/In\(_x\)Ga\(_{1-x}\)Sb superlattices for long- and very long-wave infrared detection are discussed. This system promises benefits over conventional technology based on Hg\(_{1-x}\)Cd\(_x\)Te, including suppressed band-to-band Auger recombination rates. Accurate \( \mathbf{K} \cdot \mathbf{p} \) band structures are used to obtain radiative, electron-electron and hole-hole band-to-band Auger, and shallow trap level assisted Auger recombination rates for n-on-p photodiodes. Calculated limits for high temperature operation of ideal photovoltaic detectors are presented. The suppression of band-to-band Auger by "band gap engineering" is predicted to lead to improved background-limited operating temperatures.

Introduction

A wide variety of remote sensing applications exist in the long and very long wave infrared (LWIR and VLWIR) spectral regions (above 8\( \mu \text{m} \)). It includes atmospheric pollution probes, astrophysical imaging, \textit{in-situ} molecular beam epitaxy growth temperature monitors, and satellite-based surveillance. InAs/In\(_x\)Ga\(_{1-x}\)Sb superlattices (SLs) have recently been examined for possible niche applications in the LWIR region because of perceived advantages over Hg\(_{1-x}\)Cd\(_x\)Te[1, 2, 3]. In this paper, we theoretically examine the wavelength region ranging from 11 to 17 \( \mu \text{m} \). Previous calculations of recombination rates have predicted superior performance of an InAs/In\(_x\)Ga\(_{1-x}\)Sb SL with an 11 \( \mu \text{m} \) cutoff due to the suppression of band-to-band Auger recombination[4]. These rate predictions have recently been confirmed experimentally[5].

Unlike GaAs-based QWIPs, the SLs have a fundamental gap and carrier lifetimes are limited by radiative and Auger recombination processes rather than the much faster hot-electron processes relevant to the GaAs systems. Unlike HgTe/CdTe SLs this system is based on mechanically superior III-V materials, such as InAs and InSb, with which the IR community has extensive previous experience. In addition, the band gap of InAs/In\(_x\)Ga\(_{1-x}\)Sb SLs is more homogeneous in the VLWIR spectral region than that of bulk Hg\(_x\)Cd\(_{1-x}\)Te due to the weaker influence of alloy potential fluctuations. Finally, tunneling currents are reduced due to greater band-edge effective masses.
Methods and Results

The theoretical evaluation of detector performance contains several components. The SL electronic band structure is evaluated with a SL $\mathbf{K} \cdot \mathbf{p}$ Hamiltonian[6], with input parameters given in Table I. The bands are found to be highly non-parabolic, and the momentum matrix elements show strong dispersion. The effective mass approximation is found to be inapplicable. Hence the bands and momentum matrix elements evaluated on a mesh are splined and used as input for radiative, band-to-band Auger, and Auger via shallow trap recombination rate calculations.

The thin-layered InAs/In$_x$Ga$_{1-x}$Sb SLs have a type-II band-edge alignment in which the electrons are localized in the InAs layers and the holes in the In$_x$Ga$_{1-x}$Sb layers. The SL is strained such that the In$_x$Ga$_{1-x}$Sb layers are under biaxial compression breaking the degeneracy of the heavy hole and light hole edges as these edges are shifted upward and downward in energy, respectively. The corresponding SL heavy and light hole bands are therefore split, and when this splitting exceeds the energy gap, Auger recombination of the carriers is suppressed in p-type material[3].

We find that AM-7 transitions are the dominant band-to-band recombination transitions involving hole-hole collisions in the 11-17 $\mu$m superlattices discussed here. An AM-7 transition involves two holes in the heavy hole band, labeled 1 and 2; an electron in the lowest conduction band, labeled 1'; and an electron in the valence band immediately below the heavy hole band (usually the light hole band), labeled 2'[7]. The dominant transitions involving electron-electron collisions are AM-1, involving two electrons and an unoccupied state in the lowest conduction band, and a hole in the heavy hole band.

The band-to-band Auger recombination rate calculation follows that described in ref. [8]. It differs from our earlier detector calculations[3] in that the average over carriers involves both electron and hole carrier distributions. Earlier calculations were limited to the evaluation of a single minority carrier lifetime in the region of highest occupation. It is important to integrate over the entire minority carrier distribution function in the longer wavelength SLs considered here because the small gaps imply that thermal minority carrier concentrations can be relatively large. The lifetime calculations are more complex, because they involve averages over both carrier distributions. For Auger recombination involving hole-hole scattering and initial state electrons in the C1 and LH1 bands, the Auger rate per unit volume is given by

$$R_A = \frac{3e^4\hbar^3}{8\pi^6 m^4 \epsilon^2} (1 - e^{-(\mu_e - \mu_h)/k_BT}) \int \int \int d^3\mathbf{K}_1 d^3\mathbf{K}_2 d^3\mathbf{K}_2'$$

$$\times f_p(E_{HH1} (\mathbf{K}_1)) f_p(E_{HH1} (\mathbf{K}_2)) f_n(E_{C1} (\mathbf{K}_1 + \mathbf{K}_2 - \mathbf{K}_2'))$$

$$\times \frac{\beta_{C1,HH1}(\mathbf{K}_1, \mathbf{K}_1') \beta_{LH1,HH1}(\mathbf{K}_2, \mathbf{K}_2')}{|\lambda^2 + |\mathbf{K}_1 - \mathbf{K}_1'|^2|}$$

$$\times \delta(E_{C1}(\mathbf{K}_1 + \mathbf{K}_2 - \mathbf{K}_2') + E_{LH1}(\mathbf{K}_2') - E_{HH1}(\mathbf{K}_1) - E_{HH1}(\mathbf{K}_2)),$$

(1)

where $\beta_{n,m}(\mathbf{K}_1, \mathbf{K}_2)$, defined in ref. [3], is associated with $\mathbf{K} \cdot \mathbf{p}$ perturbations of the wave functions in band $n$ with wave vector $\mathbf{K}_1$ and $m$ with wave vector $\mathbf{K}_2$; $\lambda$ is the reciprocal Debye screening length; $\epsilon$ is the static dielectric constant; $f_n$ and
$f_p$ are the electron and hole Fermi-Dirac occupation functions, respectively; and $\mu_e$ and $\mu_h$ are the electron and hole quasichemical potentials respectively. Expression (1) is obtained from equation (1) of ref. [9] by averaging over the initial and final spin orientations[10] and replacing bulk variables by equivalent superlattice ones. The average Auger lifetime per carrier is given by $\tau_A = \Delta n/R_A$, where $\Delta n$ is the density of nonequilibrium minority carriers. To evaluate (1), a small $\Delta n$ is generated by a small upward shift of $\mu_e$ relative to the equilibrium chemical potential, with the downward shift of $\mu_h$ calculated from the condition of charge conservation. Performing the integral over the energy conserving delta function analytically and exploiting rotational invariance in the in-plane direction results in the reduction of eqn. (1) from nine to seven nested integrals. These are numerically evaluated.

The calculation of the total radiative recombination rate per unit volume follows from equations (3.2.34) and (3.2.36) in ref. [11] by evaluating one of the momentum and the energy integrals, and replacing bulk variables by equivalent superlattice ones. The result is

$$R_R = \frac{e^2 \mu}{\pi^3 m^2 \hbar^2 c^3} \int d^3K (E_{C1}(K) - E_{HH1}(K)) f_n(E_{C1}(K)) f_p(E_{HH1}(K))$$

$$\times |\langle C1, K|p|HH1, K\rangle|^2,$$

where $\mu$ is the index of refraction.

The evaluation of Auger recombination via traps in SLs is considered next. In contrast to band-to-band processes, Auger recombination of optically generated minority carriers (density $\Delta n$) may also involve one or another of the shallow donor or acceptor levels giving rise to the extrinsic carrier concentration. The formalism for this class of non-radiative transitions in bulk semiconductors has been previously considered by Bess[12], and Sinha and DiDominico[13]. Calculations based on Bess' formalism have been reported by Dutta and Nelson[14]. Our formalism is necessarily different due to the consideration of SLs. We focus on n-on-p photovoltaic devices, and consider recombination via acceptors in the p-type layer. Following Bess, we assume that the minority carrier wave function may be approximated by a plane wave, and the acceptor wave function by a ground-state hydrogenic wave function. Averaging over spin orientations gives the SL Auger recombination rate per unit volume via acceptors involving, for example, initial state electrons in the C1 and HH1 bands

$$R_T = \frac{16 \beta^5 e^4 N_A}{\pi^5 c^2 \hbar} f_p(E_A) \left[ 1 - e^{-(\mu_e - \mu_h)/kT} \right]$$

$$\times \int dK' dK_2 dK_2' \left[ 1 - f_p(K_2') \right] f_p(K_2) f_n(K_1') \frac{1}{\left( \beta^2 + |K_1' + K_2' - K_2|^2 \right)^4}$$

$$\times \frac{1}{[\lambda^2 + |K_2 - K_2'|^2]^2} \delta(E_{C1}(K') + E_{LH1}(K') - E_A - E_{HH1}(K_2)), (3)$$

where $\beta = 2eE_A/e^2$ is the reciprocal range of the acceptor hydrogenic wave function; $E_A$ is the acceptor ionization energy; $N_A$ is the number of acceptors per unit volume; and $f_p(E_A)$ refers to the probability of an acceptor state being unoccupied. The zero of the energy scale is chosen to be the top of the valence band.
An expression similar to (1) for AM-1 transitions may be derived with the same methods. Also, Auger recombination via donors in superlattices are described by an expression similar to (3). We obtain the total recombination rate by summing the rates due to hole-hole and electron-electron band-to-band Auger recombination, Auger recombination via acceptors and donors, and radiative recombination.

Figure 1 plots calculated values of $D^*$ for several 11 to 17 $\mu$m SLs and 11 $\mu$m bulk Hg$_x$Cd$_{1-x}$Te photovoltaic detectors, as a function of temperature. These theoretical maximum values of $D^*$ were obtained from the expressions $D^* = (\eta/2hv)(\tau_n/n_pL_n)^{1/2}$ for n-on-p photodiodes, and $D^* = (\eta/2hv)(\tau_p/p_nL_p)^{1/2}$ for p-on-n photodiodes[15]. Here $\eta$ is the quantum efficiency given by $L_{(n,p)}\alpha/(L_{(n,p)}\alpha + 1)$[16]. The minority carrier diffusion length, $L_{(n,p)}$, is proportional to $\tau^{1/2}$ so that $D^*$ is proportional to $\tau^{1/4}$. The vertical electron mobility employed in SL calculations is listed in Table I. All other parameters are defined and given in refs. [4] and [15]. Calculated detectivities are theoretical upper bounds due to the neglect of other recombination mechanisms such as Shockley-Read.

For a photodiode in which the minority carrier lifetimes are dominated by band-to-band Auger recombination ($\tau \propto (\text{minority carrier density})^{-2}$[15]), the detectivity is approximately independent of doping (weak doping dependence enters from $\eta$). However, if the minority carrier lifetimes are dominated by radiative recombination ($\tau \propto (\text{minority carrier density})^{-1}$[15]), the detectivity is proportional to $\eta/(\text{minority carrier density})^{1/4}$. In the latter case, increasing doping will increase the detectivity until band-to-band Auger recombination or the decreasing quantum efficiency start to dominate.

The optimum 11 $\mu$m superlattice is found to be 39.8ÅInAs/15ÅIn$_x$Ga$_{1-x}$Sb, due to the large strain-induced splitting of the HH1 and LH1 bands suppressing hole-hole band-to-band Auger recombination[4]. The detectivity is enhanced in this system by doping the p-type side of n-on-p photodiodes to a level where band-to-band Auger recombination rates just begin to exceed radiative rates, corresponding to an acceptor density of about $N_A=10^{17}$cm$^{-3}$. The optimum detectivities of 11 $\mu$m HgCdTe are obtained for p-on-n photodiodes with a doping on the n-type side of $N_D=10^{15}$cm$^{-3}$, a level at which band-to-band Auger and radiative lifetimes are comparable at cryogenic temperatures. Upper bounds on detectivities for HgCdTe based on our band structure and lifetime calculations are plotted in Fig. 1, and agree well with those predicted by Kinch and Borrello[15]. 11 $\mu$m HgCdTe detectivities are predicted to be lower than the upper bounds predicted for the optimum 11 $\mu$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.

We conclude that IR detector performance of InAs/In$_x$Ga$_{1-x}$Sb SLs is at least as good as bulk Hg$_x$Cd$_{1-x}$Te at 11 $\mu$m. The high predicted detectivities for InAs/In$_x$Ga$_{1-x}$Sb SLs with gaps ranging from 13 to 17 $\mu$m, as well as appreciable producibility and performance advantages relative to HgCdTe, suggest that they are promising for VLWIR detector applications. Their use may give rise to significant savings in the size, weight, power, and lifetime of device coolers. This is of particular
significance in the VLWIR spectral region due to the considerable cooling required to achieve typical background limited performance. Of further benefit is their compatibility with III-V electronics, good material strength, and insensitivity to alloy potential fluctuations.

Acknowledgements

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References


**Table I-Input Parameters for Band Structure and Detectivity Calculations**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GaSb</th>
<th>InSb</th>
<th>InAs</th>
<th>In$<em>{0.25}$Ga$</em>{0.75}$Sb</th>
<th>InAs/InGaSb</th>
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<tr>
<td>lattice constant $^1$ (Å)</td>
<td>6.096</td>
<td>6.479</td>
<td>6.058</td>
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<tr>
<td>a deformation potential $^1$ (eV)</td>
<td>-7.2</td>
<td>-7.7</td>
<td>-5.8</td>
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<tr>
<td>b deformation potential $^1$ (eV)</td>
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<td>-2.0</td>
<td>-1.8</td>
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<td></td>
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<tr>
<td>$c_{11}^1$ (10$^{11}$ dyn cm$^{-2}$)</td>
<td>8.834</td>
<td>6.918</td>
<td>8.329</td>
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<tr>
<td>$c_{12}^1$ (10$^{11}$ dyn cm$^{-2}$)</td>
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<td>3.788</td>
<td>4.526</td>
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<td>energy gap $^1$ (eV)</td>
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<td>0.4180</td>
<td>0.5913</td>
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<tr>
<td>spin orbit splitting $\Delta^1$ (eV)</td>
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<tr>
<td>$m^*_{hh}$ in (100) direction$^2$</td>
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<td>$m^*_{ee}$ averaged $^1$</td>
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<tr>
<td>$\frac{2}{m^*}</td>
<td>P_{hh,c}^2</td>
<td>^3$ (eV)</td>
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<td>$\perp$ electron mobility$^5$ (cm$^2$/V·s)</td>
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<td>1000</td>
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</table>

Notes: All values are at T=0K. Hydrostatic deformation potentials of the valence bands are neglected. All parameters for In$_{0.25}$Ga$_{0.75}$Sb are linearly interpolated from InSb and GaSb unless otherwise noted in the In$_{0.25}$Ga$_{0.75}$Sb column. The superlattice is assumed to be grown on a GaSb substrate.


3 Momentum matrix element deduced from $m^*_{ee}$ of InAs and GaSb.

4 Gives best agreement with measured gaps (R.H. Miles et al., Appl. Phys. Lett. 57, 801 (1990)).

5 R. Miles, private communication.
Figure 1. Calculated upper bounds to photovoltaic detectivities of several 11-17 \( \mu \text{m} \) InAs/In\textsubscript{x}Ga\textsubscript{1-x}Sb superlattices and 11 \( \mu \text{m} \) Hg\textsubscript{1-z}Cd\textsubscript{z}Te, as a function of temperature. The SL data is for n-on-p photodiodes, and the HgCdTe data for p-on-n photodiodes. The doping level of the lower layer is indicated in each case.