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"SMALL BAND GAP SUPERLATTICES AS INTRINSIC LONG WAVELENGTH INFRARED DETECTOR MATERIALS"

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Intrinsic long wavelength ($\lambda \geq 10\ \mu m$) infrared (IR) detectors are currently made from the alloy (Hg, Cd) Te. There is one parameter, the alloy composition, which can be varied to control the properties of this material. The parameter is chosen to set the band gap (cut-off wavelength). The (Hg, Cd) Te alloy has the zincblend crystal structure. Consequently, the electron and light-hole effective masses are essentially inversely proportional to the band gap whereas the heavy-hole effective mass is essentially independent of the band gap. As a result, the electron and light-hole effective masses are very small ($M_c^*/M_o \sim M_{lh}/M_o \leq 0.01$) whereas the heavy-hole effective mass is ordinary size ($M_{hh}^*/M_o \sim 0.4$) for the alloy compositions required for intrinsic long wavelength IR detection. This combination of effective masses leads to rather easy tunneling and relatively large Auger transition rates. These are undesirable characteristics, which must be designed around, of an IR detector material. They follow directly from the fact that (Hg, Cd) Te has the zincblend crystal structure and a small band gap.

In small band gap superlattices, such as HgTe/CdTe, In(As, Sb)/InSb and InAs/(Ga,In)Sb, the band gap is determined by the superlattice layer thicknesses as well as by the alloy composition (for superlattices containing an alloy). The effective masses are not directly related to the band gap and can be separately varied. In addition, both strain and quantum confinement can be used to split the light-hole band away from the valence band maximum. These "band structure engineering" options can be used to reduce tunneling probabilities and Auger transition rates compared with a small band gap zincblend structure material. We discuss the different "band structure engineering" options for the various classes of small band gap superlattices.

SMALL BAND-GAP SUPERLATTICES AS INTRINSIC IR DETECTOR MATERIALS

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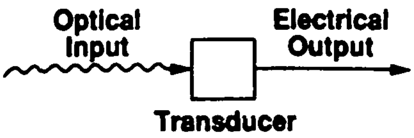
OUTLINE

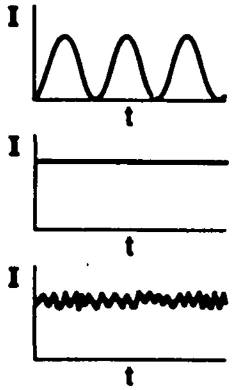
1) Introduction
2) Band structure engineering
    a) Zincblende structure materials
    b) Small band-gap superlattices
3) An example InAs/GaInSb
4) Conclusion

IR DETECTORS



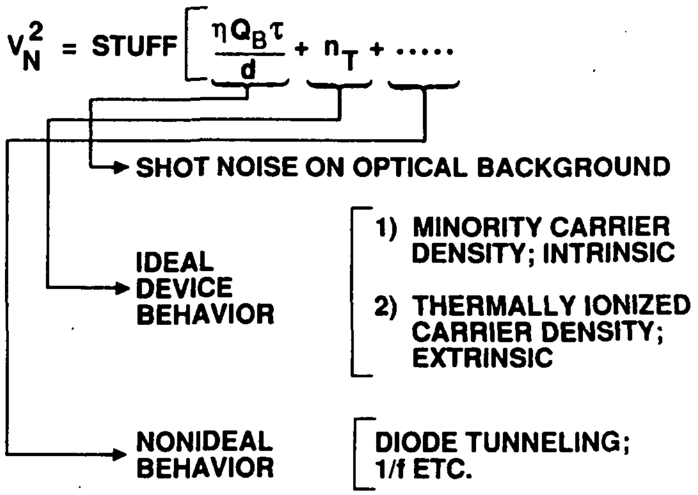
Optical Input

1) Signal
2) Background
3) Shot noise on background



$$V_N = \left[V_1^2 + V_2^2 + \cdots \right]^{1/2}$$

BEST TRANSDUCER DOESN'T DEGRADE S/N (BACKGROUND LIMITED)



$$V_N^2 = \mathrm{STUFF} \left[\underbrace{\frac{\eta Q_B \tau}{d}} + \underbrace{n_T} + \underbrace{\cdots\cdots} \right.$$

SHOT NOISE ON OPTICAL BACKGROUND

IDEAL DEVICE BEHAVIOR
1) MINORITY CARRIER DENSITY; INTRINSIC
2) THERMALLY IONIZED CARRIER DENSITY; EXTRINSIC

NONIDEAL BEHAVIOR
DIODE TUNNELING; 1/f ETC.

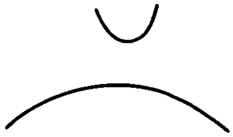
Want $\frac{\eta Q_B \tau}{d} > n_T$

Min $\frac{n_T}{\alpha \tau}$

$d \sim \alpha^{-1}$

$\sim e^{-E_t\, kT}$

BAND STRUCTURE PARAMETERS



PARAMETERS	PHYSICAL PROCESS
E_g	ABSORPTION THRESHOLD
$M_e^* \, (M_\perp ; M_{\parallel})$	RECOMBINATION TIMES (AUGER; RADIATIVE)
$M_h^* \, (M_\perp ; M_{\parallel})$	ABSORPTION COEFFICIENT
P_{eh}	TRANSPORT (TUNNELING; DIFFUSION)

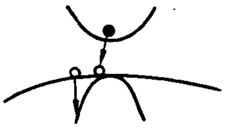
DESIGN PROCESS

1) MATERIAL DESIGN
2) DEVICE DESIGN

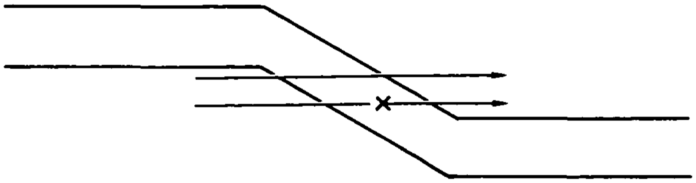
AVOIDABLE PROCESSES

AUGER

$$e^{-\frac{E_g}{kT}\,\frac{M_e}{M_h}}$$



TUNNELING



K•P THEORY

$$\left[\frac{P^2}{2M} + V\right] \psi = \epsilon \psi$$

$$\psi = e^{i k \cdot r}\, U^k$$

$$\left[\frac{P^2}{2M} + \frac{\hbar k \cdot P}{M} + \frac{(\hbar k)^2}{2M} + V\right] U^k = \epsilon\, U^k$$

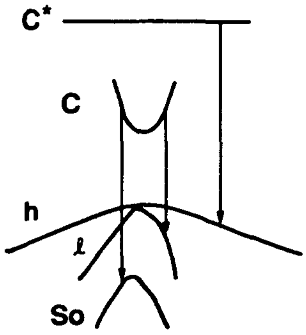
AT ZONE CENTER (k = o)

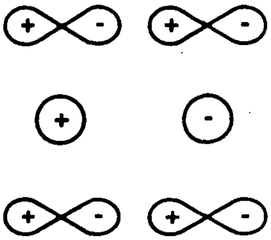
$$\left[\frac{P^2}{2M} + V\right] U_j^o = \epsilon_j^o\, U_j^o$$

$$U = \sum_j a_j\, u_j^o$$

$$0 = \sum_j \left[\left(\epsilon_j^o + \frac{(\hbar k)^2}{2M} - \epsilon\right) \delta_{ij} + \frac{\hbar \vec{k}\cdot}{M} \langle U_i \,|\vec{P}|\, U_j\rangle\right] a_j$$

ZINCBLENDE STRUCTURE MATERIALS



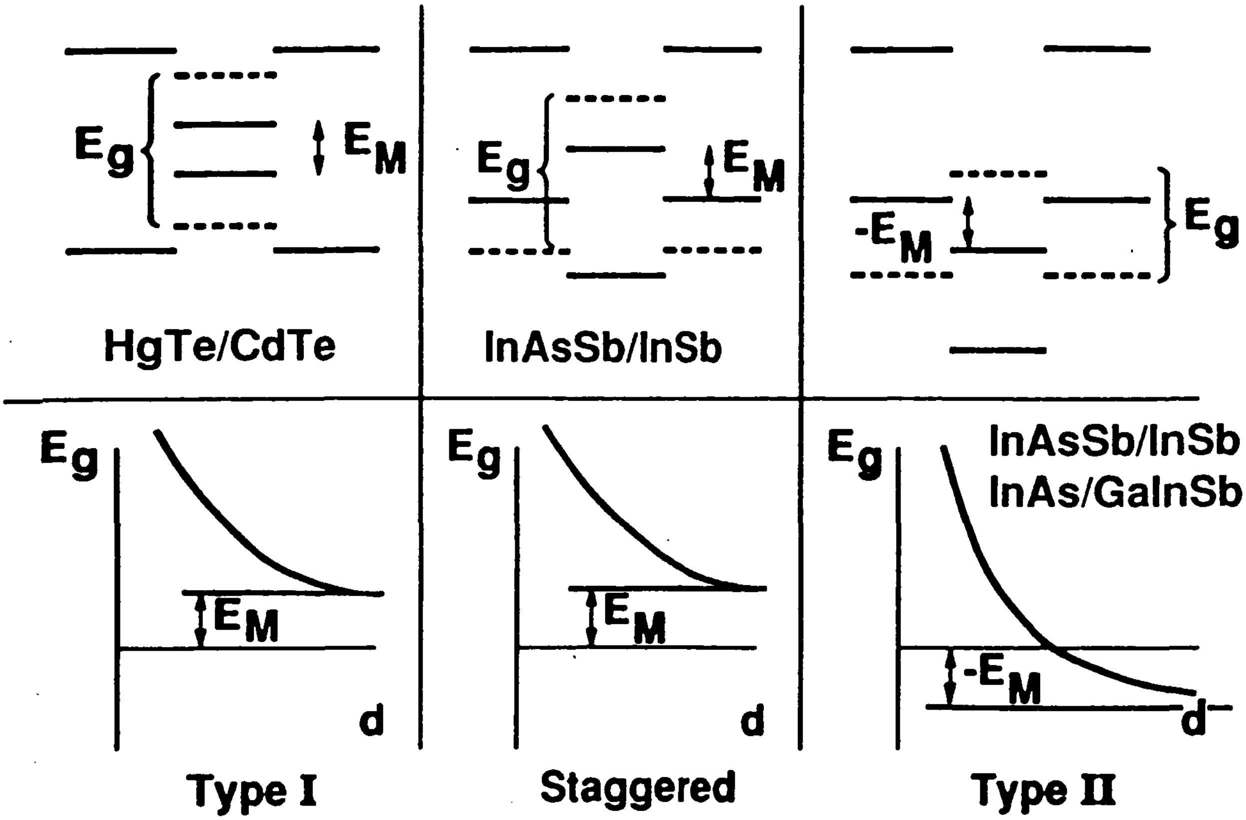


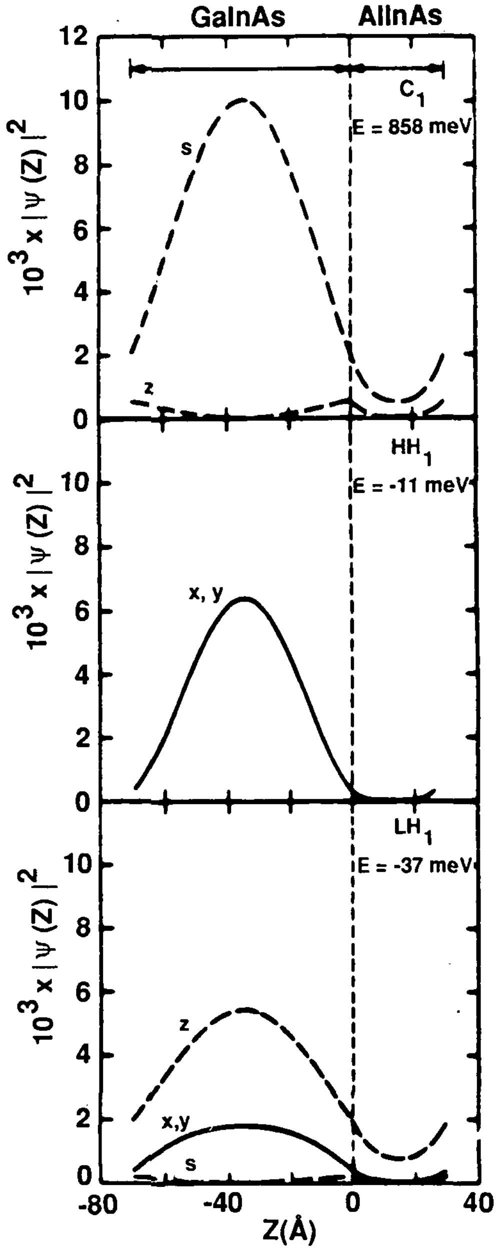
ELECTRON AND LIGHT HOLE $\begin{pmatrix}\text{SMALL } E_g \\ \text{LARGE } \Delta\end{pmatrix}$

$$\begin{vmatrix} \epsilon_c - \epsilon & \alpha \\ \alpha^* & \epsilon_v - \epsilon \end{vmatrix} = 0 \qquad \alpha = \sqrt{\frac{2}{3}}\, iPk$$

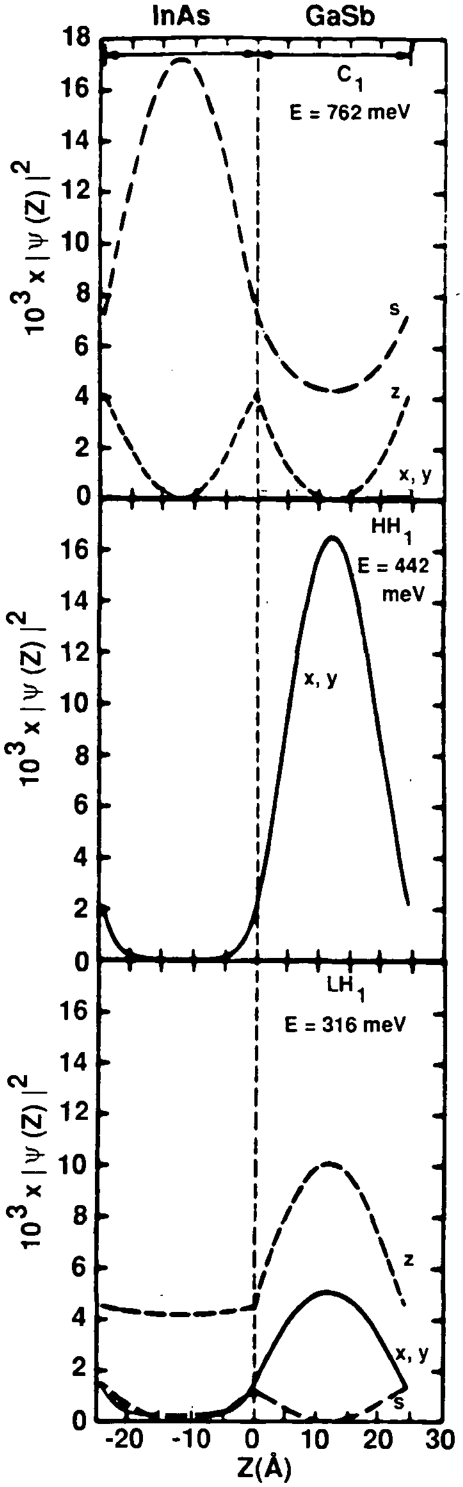
$$\frac{M_o}{M^*} = \pm \frac{2M}{\hbar^2} \quad |P|^2 \quad \left(\frac{2}{3}\boxed{\frac{1}{E_g}}\right)$$

SMALL BANDGAP SUPERLATTICES



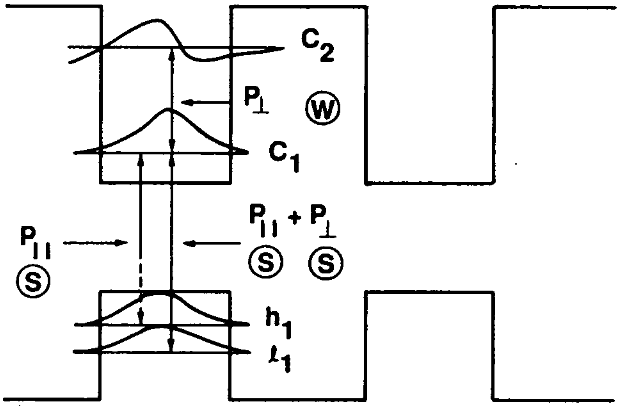


TYPE I



TYPE II

K•P THEORY SUPERLATTICE SIMPLE CASE



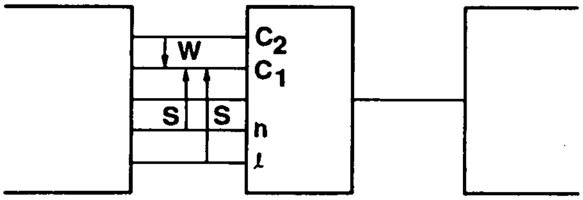
$\Psi = F\,U$

$\langle F_1 U_1 | P | F_2 U_2 \rangle$

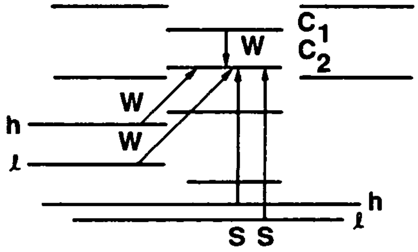
$\sim \langle F_1 | F_2 \rangle \langle U_1 | P | U_2 \rangle$ S

$+ \langle F_1 | P | F_2 \rangle \langle U_1 | U_2 \rangle$ W

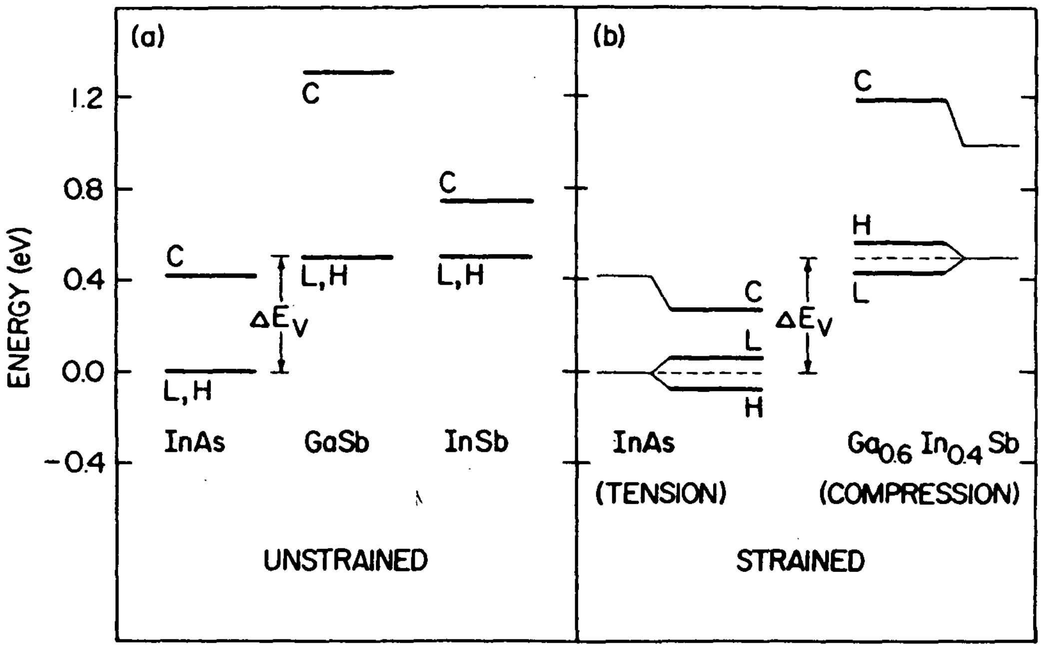
K•P THEORY SUPERLATTICE SMALL GAP

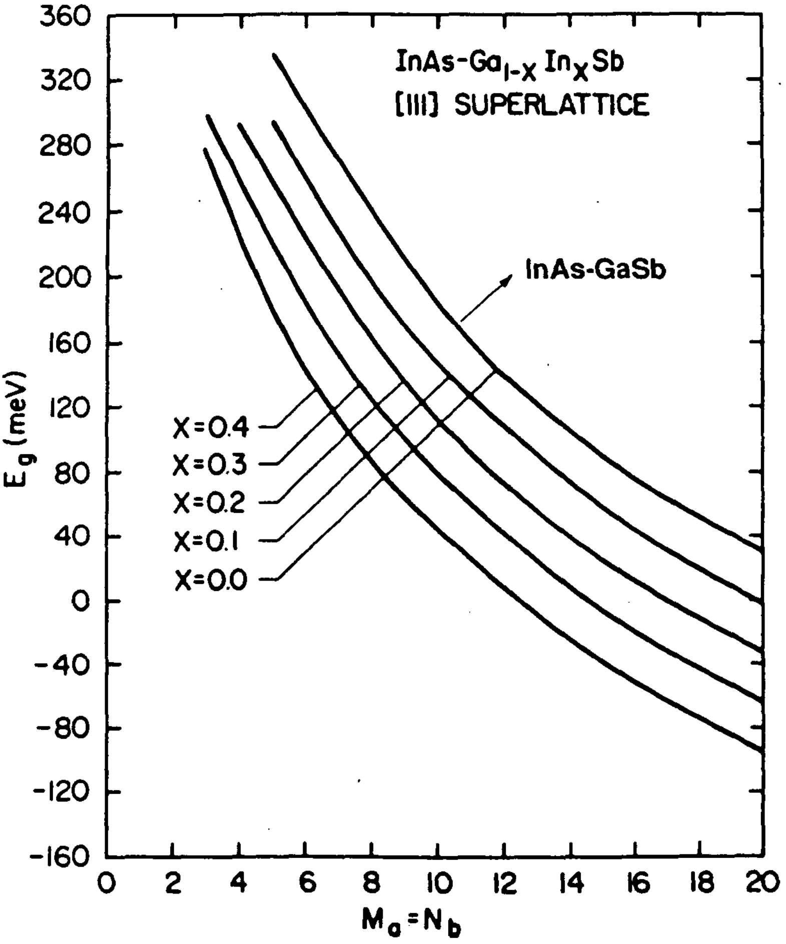


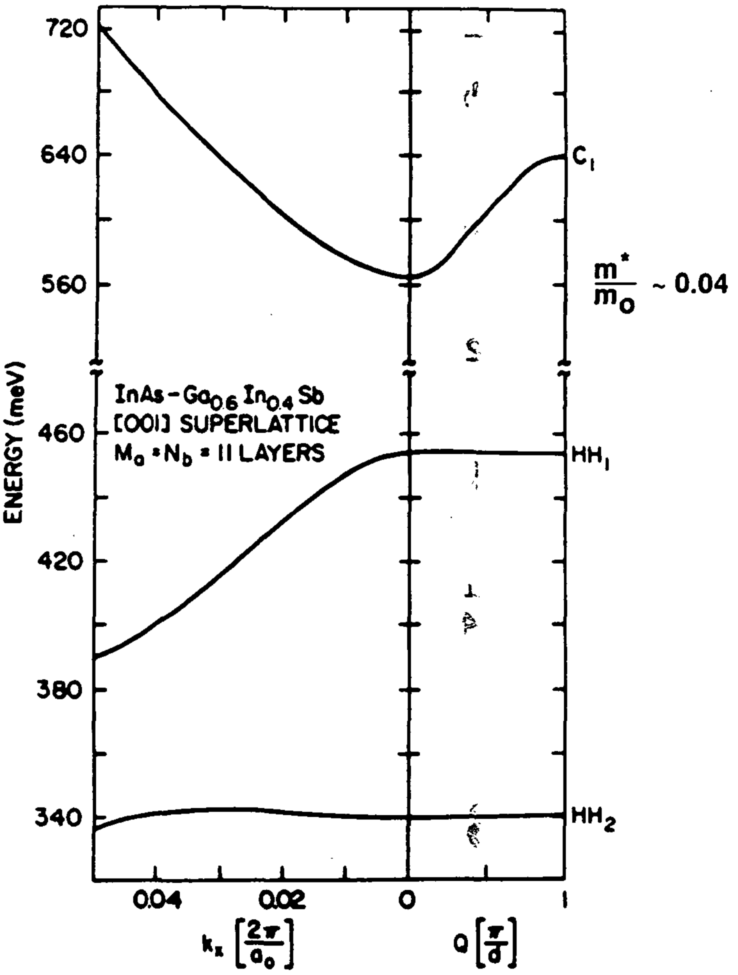
HgTe/CdTe

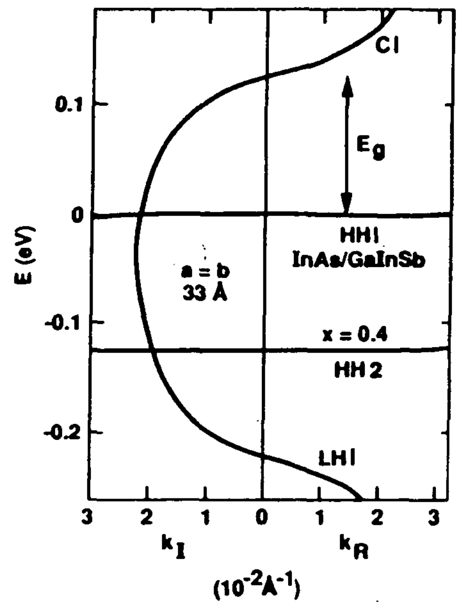


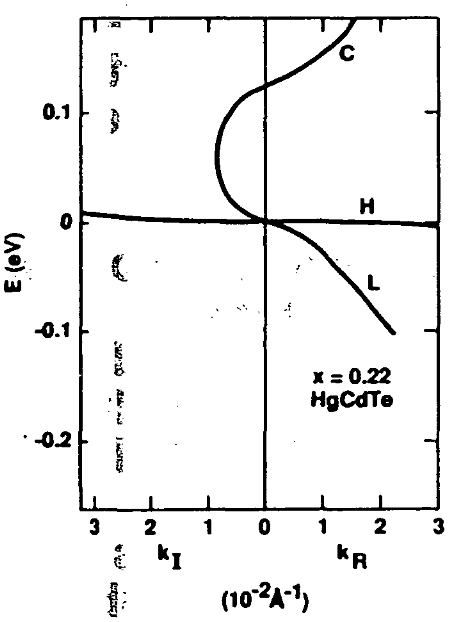
TYPE II

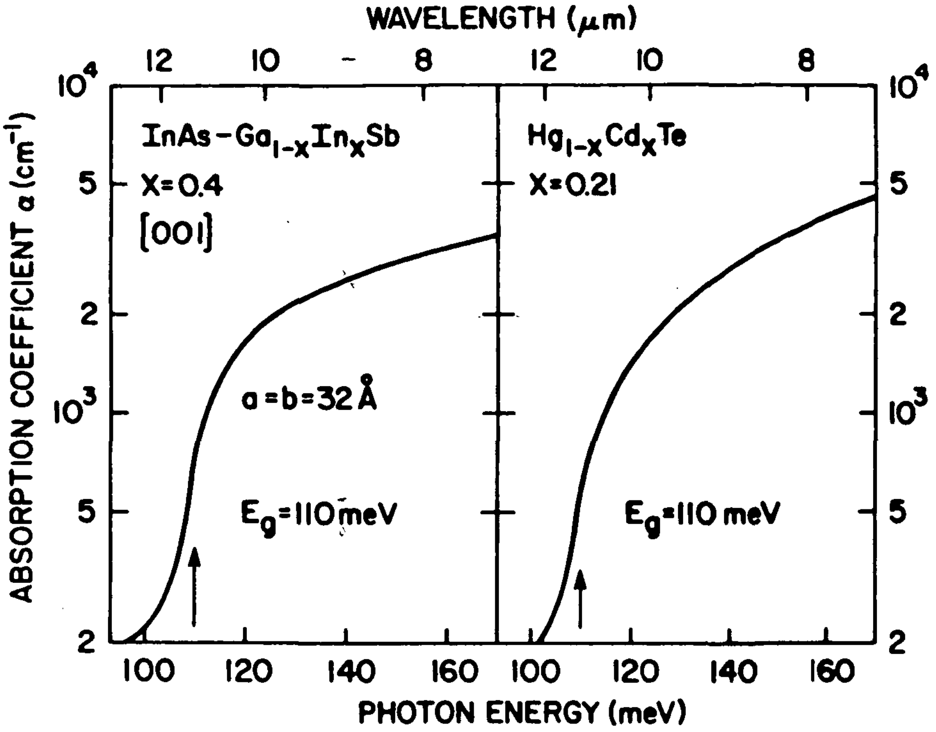

(a)
(b)
ENERGY (eV)
1.2
0.8
0.4
0.0
-0.4
C
L,H
ΔE_V
InAs
GaSb
InSb
UNSTRAINED
H
L
InAs
(TENSION)
$Ga_{0.6}In_{0.4}Sb$
(COMPRESSION)
STRAINED


InAs-$Ga_{1-X}In_XSb$
[111] SUPERLATTICE
InAs-GaSb
X=0.4
X=0.3
X=0.2
X=0.1
X=0.0
E_g (meV)
360
320
280
240
200
160
120
80
40
0
-40
-80
-120
-160
0
2
4
6
8
10
12
14
16
18
20
$M_a = N_b$


720
640
560
460
420
380
340
ENERGY (meV)
InAs-Ga$_{0.6}$In$_{0.4}$Sb
[001] SUPERLATTICE
$M_a = N_b = 11$ LAYERS
C_1
$\frac{m^*}{m_0} \sim 0.04$
HH_1
HH_2
0.04
0.02
0
1
$k_x\left[\frac{2\pi}{a_0}\right]$
$Q\left[\frac{\pi}{d}\right]$


0.1
0
-0.1
-0.2
E (eV)
C1
E_g
HH1
InAs/GaInSb
a = b
33 Å
x = 0.4
HH2
LH1
3
2
1
0
1
2
3
k_I
k_R
(10^{-2}Å^{-1})


0.1
0
-0.1
-0.2
E (eV)
C
H
L
x = 0.22
HgCdTe
3
2
1
0
1
2
3
k_I
k_R
(10^{-2}Å^{-1})



SUMMARY

1) Small band-gap superlattices offer band structure engineering options which make them interesting IR materials

2) Examples of such superlattices include:
   a) HgTe/CdTe
   b) InAsSb/InSb
   c) InAs/GaInSb

3) Predictions on Eg and α in InAs/GaInSb