Intersubband absorption in $Si_{1-x}Ge_x$/Si superlattices for long wavelength infrared detectors

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ABSTRACT

We have calculated the absorption strengths for intersubband transitions in n-type $Si_{1-x}Ge_x$/Si superlattices. These transitions can be used for the detection of long-wavelength infrared radiation. A significant advantage in $Si_{1-x}Ge_x$/Si superlattice detectors is the ability to detect normally incident light; in $Ga_{1-x}Al_xAs$/GaAs superlattices intersubband absorption is possible only if the incident light contains a polarization component in the growth direction of the superlattice. We present detailed calculations of absorption coefficients, and peak absorption wavelengths for [100], [111] and [110] $Si_{1-x}Ge_x$/Si superlattices. Peak absorption strengths of about 2000-6000 cm^{-1} were obtained for typical sheet doping concentrations ($\approx 10^{12}$ cm^{-2}). Absorption comparable to that in $Ga_{1-x}Al_xAs$/GaAs superlattice detectors, compatibility with existing Si technology, and the ability to detect normally incident light make these devices promising for future applications.

Intersubband Absorption in Si/Ge Superlattices for Long Wavelength Infrared Detectors

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Si/Ge Multi Quantum Wells for LWIR detection

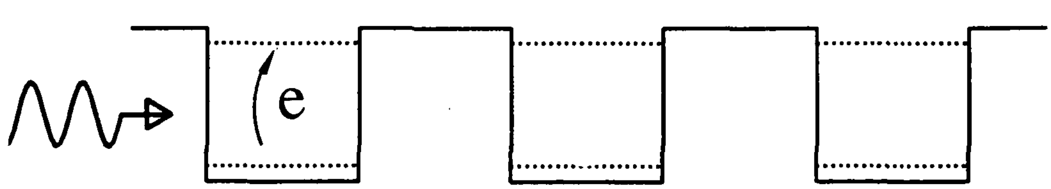
- Similar to extrinsic Si detectors
- Can change wavelength response by varying layer thicknesses
- Possible to achieve absorption at normal incidence
- Can achieve high doping concentrations
- Improved uniformity
- Compatibility with Si readout electronics

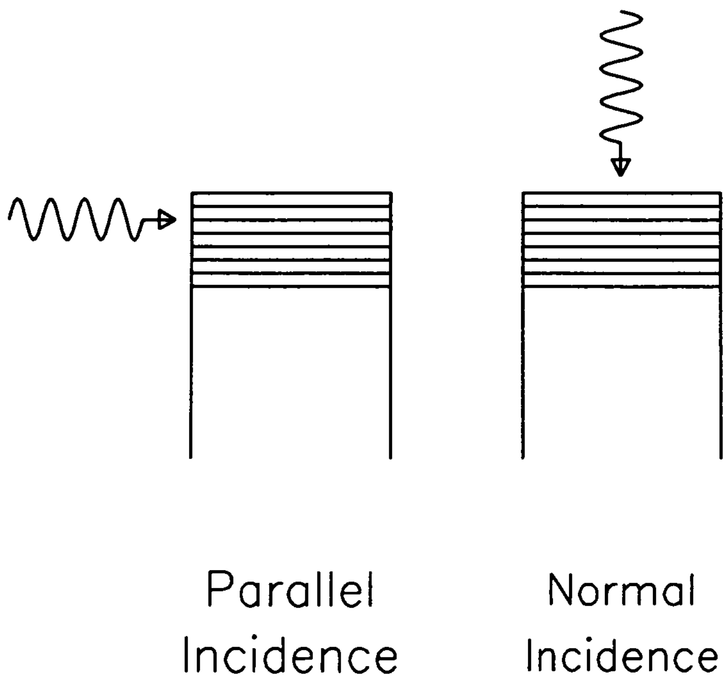
Outline

- Introduction
- Possibilities with [111],[110][1] directions
- Intersubband absorption coefficient
- Si/Ge band offsets
- Strain effects
- Results
- Conclusions

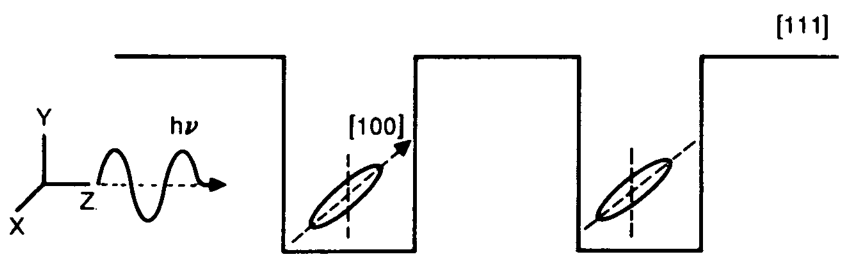
[1]C. L. Yang, D. S. Pan and R. Somoano, J. Appl. Phys. **65**, 3253 (1989).

QW Absorption





Quantum well states of ellipsoidal valley materials



Consider the case where ellipsoids are not oriented in the growth direction

- Effective mass is a tensor; large anisotropy
- Possible to couple orthogonal components of vector potential and electron motion

Optical Matrix Element in Superlattices / Multi Quantum Wells

$$M_{op} = (\frac{e}{mc})\langle U_1F_1|\vec{A}\cdot\vec{P}|U_2F_2\rangle$$

- Interband Case: V → C

$$M_{op} \sim (\frac{e}{mc})\langle U_C|\vec{A}\cdot\vec{P}|U_V\rangle\langle F_C|F_V\rangle$$

- Intersubband Case: C1 → C2

$$M_{op} \sim (\frac{e}{mc})\langle F_{C1}|A_i(\frac{1}{m^*})_{ij}P_j|F_{C2}\rangle$$

Normal Absorption

$$\alpha(\omega) \approx \left(\frac{e_x}{m^*_{xz}} + \frac{e_y}{m^*_{yz}} + \frac{e_z}{m^*_{zz}}\right)^2$$

- $1/m^*_{xz}$ and $1/m^*_{yz} \neq 0$ necessary
- shearing terms of the reciprocal effective mass tensor are important.
- large eccentricity improves absorption

Si/Ge system

- SiGe alloys; X valleys, Si conc. $x < 0.85$
- SiGe alloys; L valleys, Ge conc. $x > 0.85$

Other systems of interest

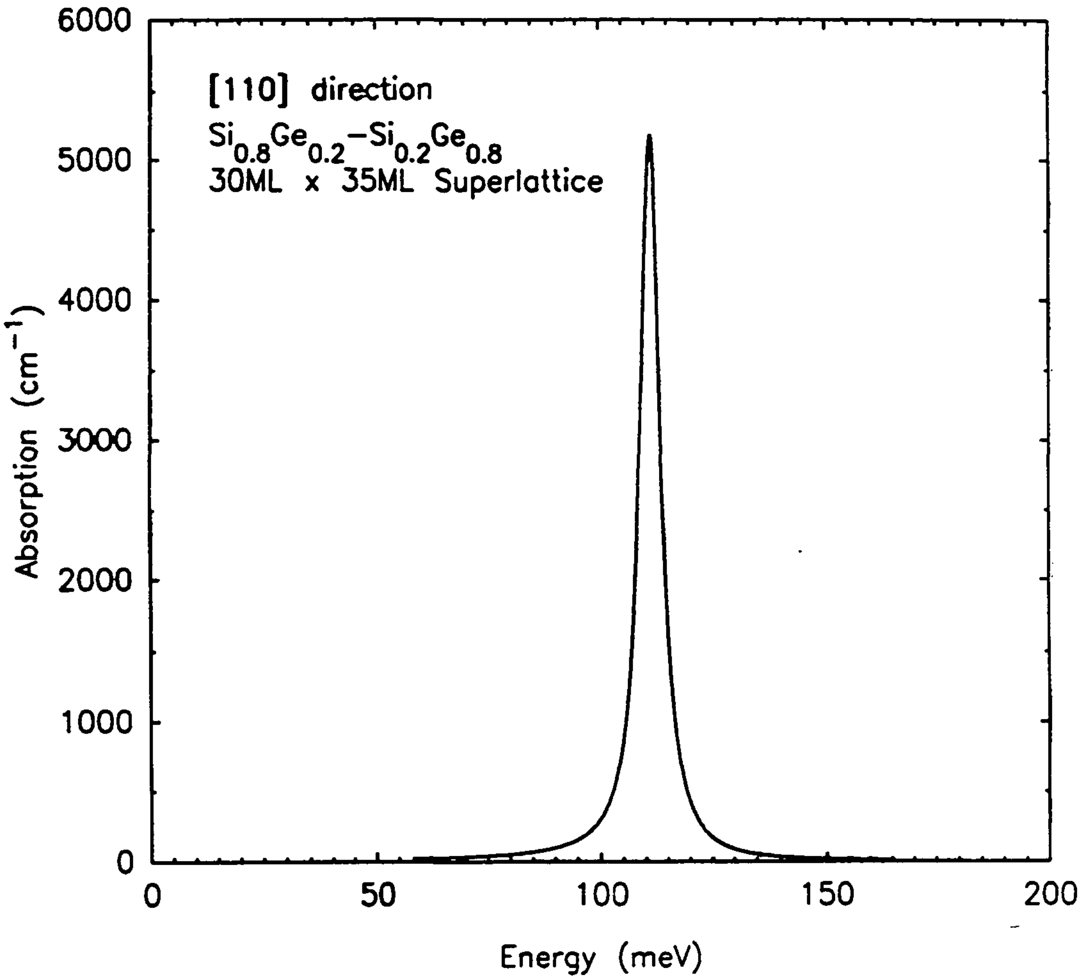
- GaAlAs alloys; X valleys, Al conc. $x > 0.45$
- GaAlSb alloys; L valleys, Al conc. $0.25 < x < 0.55$
- GaAlP, PbSnTe

Absorption

$$\alpha(w) = \frac{4\pi e^2 \hbar^2}{n m^2 c w} N_S \left| \langle F_2(z) \nabla_z F_1(z) \rangle \right|^2 \left(\frac{e_x}{m^*_{xz}} + \frac{e_y}{m^*_{yz}} + \frac{e_z}{m^*_{zz}} \right)^2$$

$$\int_0^{\pi/L} \frac{\Gamma / 2\pi}{(\hbar w - E(k_z))^2 + \Gamma^2/4} dk_z$$

- Γ is the broadening due to lifetime $\approx$ (5 meV)
- Absorption depends on m^*. Shearing terms m^*_{xz} and m^*_{yz} important
- e_j denotes the polarization direction of light
- N_S is the sheet doping concentration
- L is the length of a superlattice unit cell
- $E(k_z)$ is the subband separation energy
- F_1 and F_2 denote envelope functions

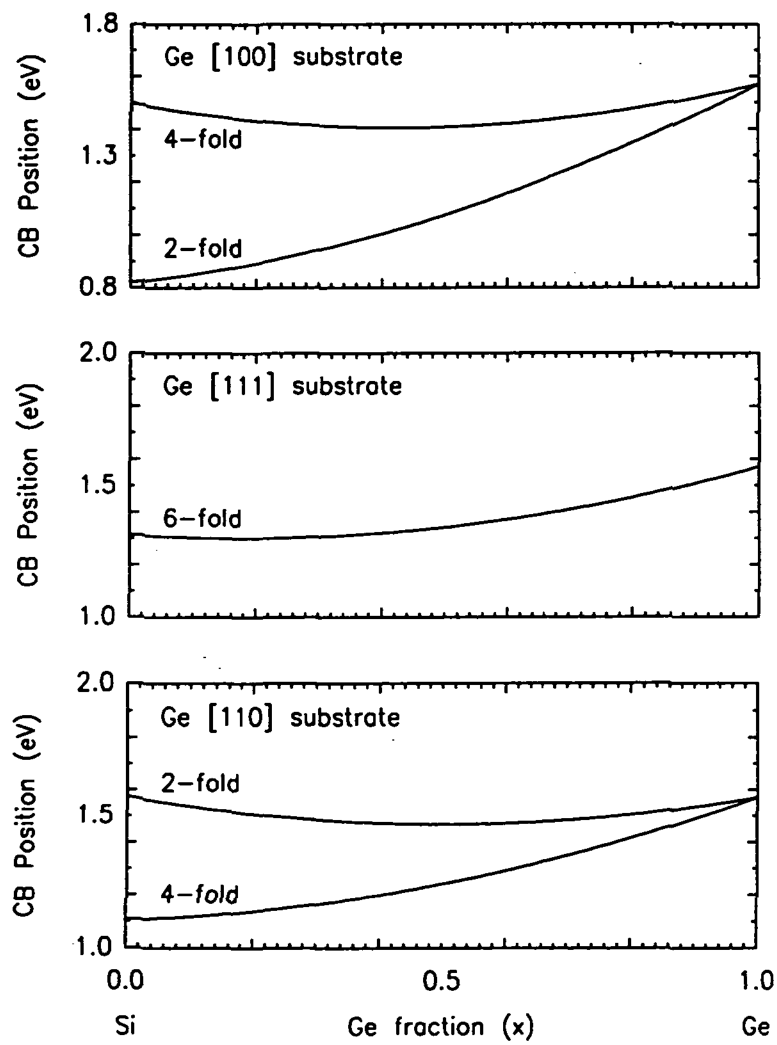


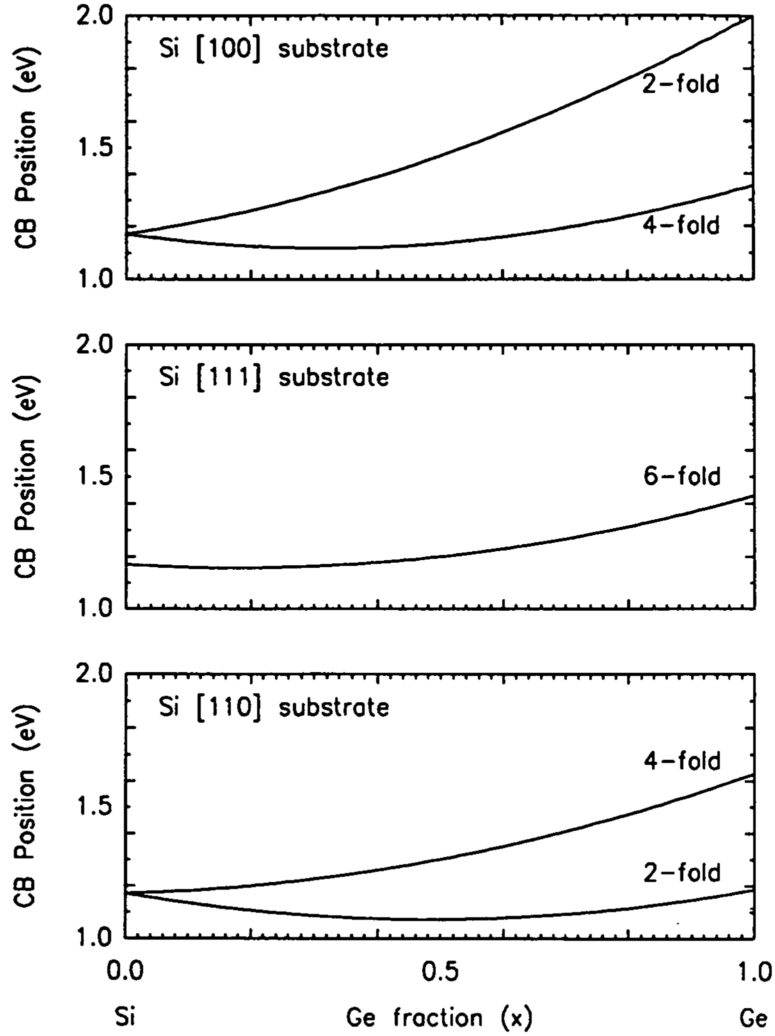
Band Offset

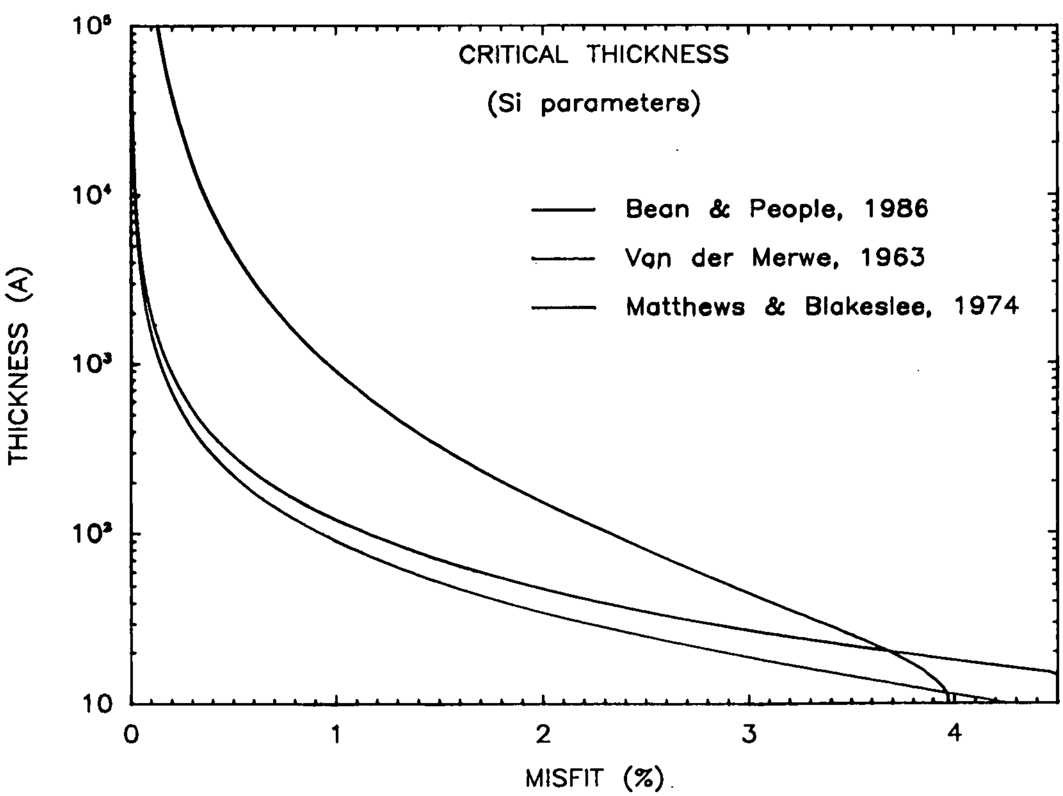
- Si/Ge average VB offset 0.54 eV
- Strain effects important
- CB offsets are small
- VB offsets are large

Strain Effects

- Lattice mismatch
- Splits the valence band degeneracy; HH and LH splitting
  - * Compression → HH shifts up
  - * Tension → LH shifts up
- Splits the conduction band degeneracy Six Δ valleys
  - * Compression → 4-fold valleys shift down
  - * Tension → 2-fold valleys shift down




Si [100] substrate
2-fold
4-fold
CB Position (eV)
Si [111] substrate
6-fold
CB Position (eV)
Si [110] substrate
4-fold
2-fold
CB Position (eV)
2.0
1.5
1.0
0.0
0.5
1.0
Si
Ge fraction (x)
Ge

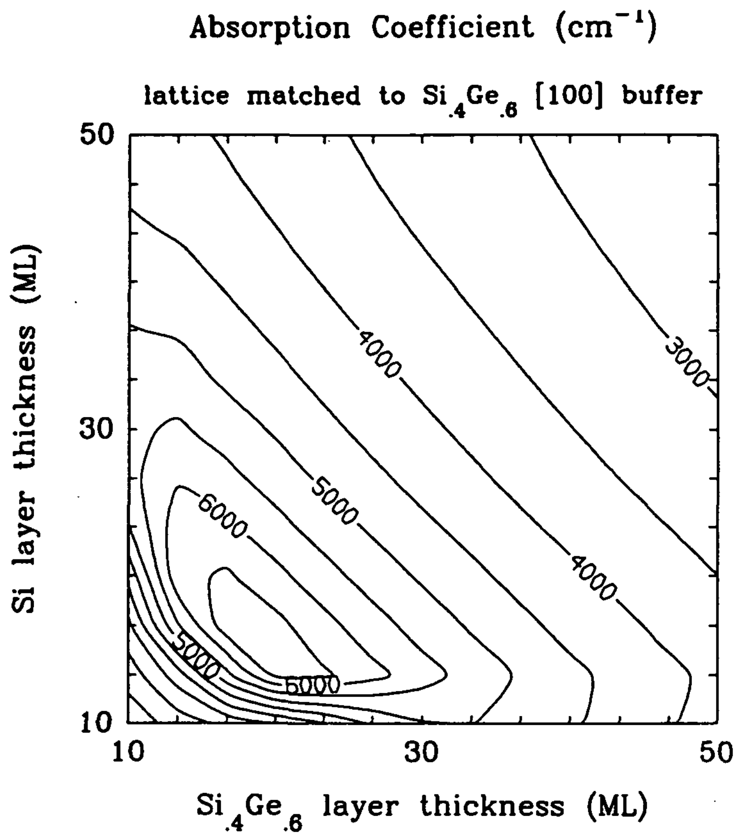

CRITICAL THICKNESS
(Si parameters)
Bean & People, 1986
Van der Merwe, 1963
Matthews & Blakeslee, 1974
THICKNESS (A)
10⁵
10⁴
10³
10²
10
0
1
2
3
4
MISFIT (%)

cases:

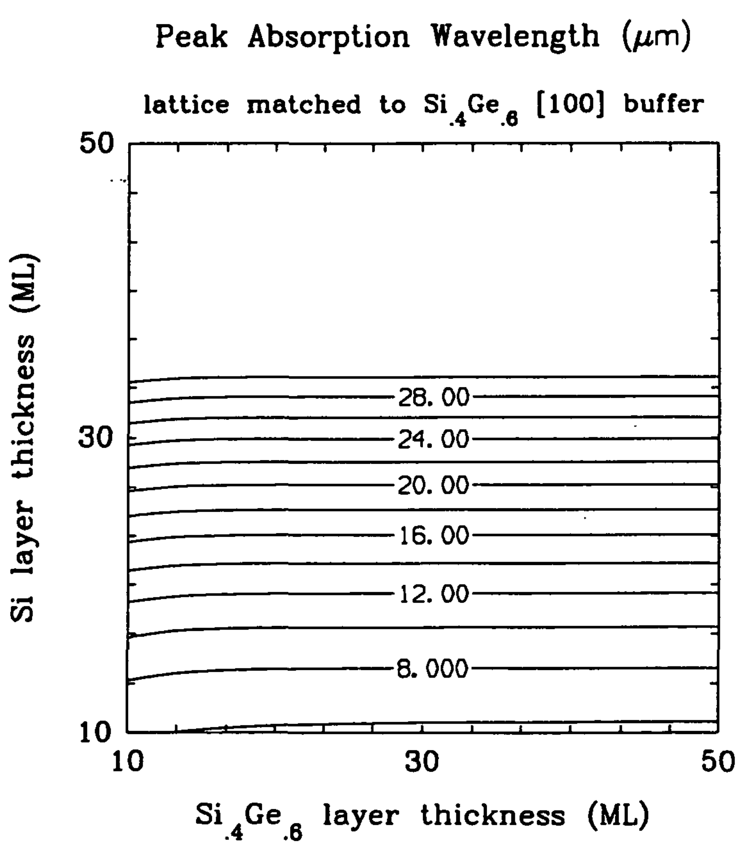
- [100] 2-fold electrons
- [100] 4-fold electrons
- [111] 6-fold electrons
- [110] 4-fold electrons

[100] direction
parallel incidence
2-fold electrons

- purpose of study is to compare with GaAs
- effective masses large
- possible to achieve good confinement
- structures:
  * barrier layer, Ge rich: $Si_{0.4}Ge_{0.6}$
  * well layer, Si rich: Si
  * coherently strained to Ge rich $Si_{0.4}Ge_{0.6}$ buffer



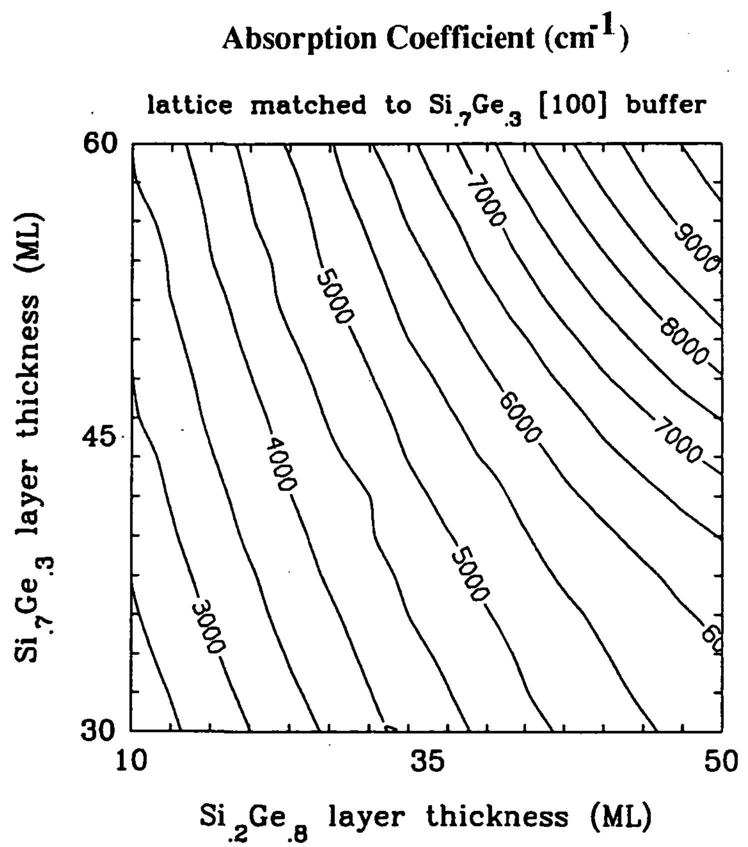
Absorption Coefficient (cm⁻¹)
lattice matched to Si.4Ge.6 [100] buffer
50
30
10
10
30
50
4000
3000
5000
6000
4000
5000
6000
Si layer thickness (ML)
Si.4Ge.6 layer thickness (ML)

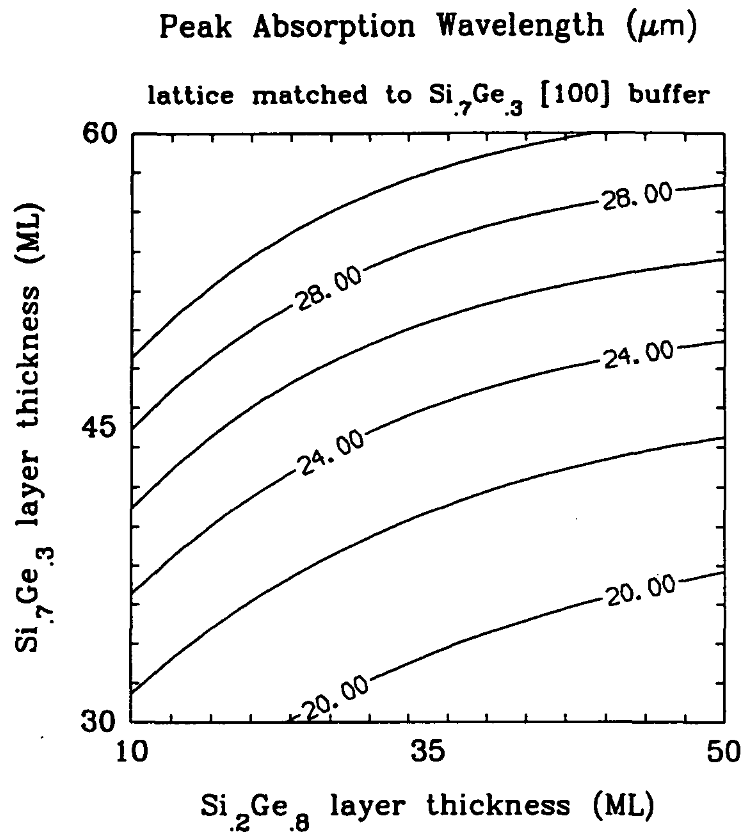


Peak Absorption Wavelength (μm)
lattice matched to Si.4Ge.6 [100] buffer
50
30
10
10
30
50
28.00
24.00
20.00
16.00
12.00
8.000
Si layer thickness (ML)
Si.4Ge.6 layer thickness (ML)

[100] direction
parallel incidence
4-fold electrons

- purpose of study is to compare with GaAs
- effective masses small
- poor confinement
- structures:
  - * barrier layer, Ge rich: $Si_{0.2}Ge_{0.8}$
  - * well layer, Si rich: $Si_{0.7}Ge_{0.3}$
  - * coherently strained to Si rich $Si_{0.7}Ge_{0.3}$ buffer





[111] direction
normal incidence
6-fold electrons

- effective masses: medium

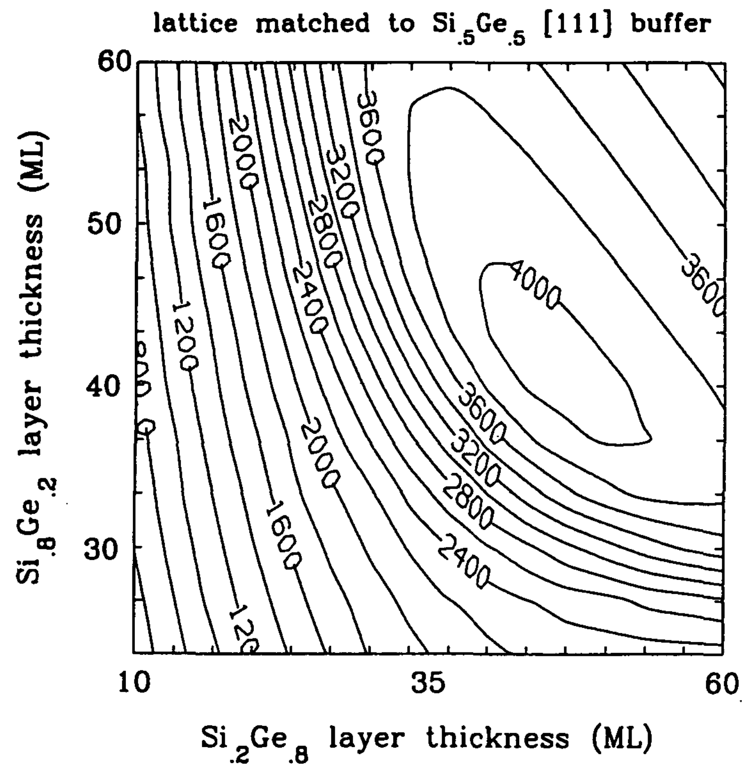
- wavefunction confinement: medium

- no preferred azimuthal dependence to absorption

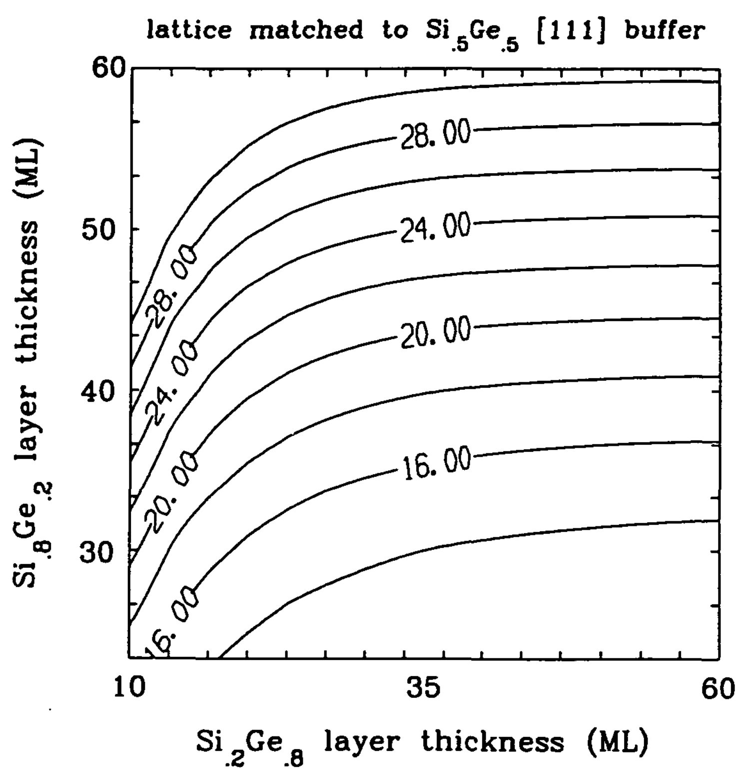
- possible to grow on a buffer layer lattice matched to free standing SL

- structures:
  * barrier layer, Ge rich: $Si_{0.2}Ge_{0.8}$
  * well layer, Si rich: $Si_{0.8}Ge_{0.2}$
  * coherently strained to $Si_{0.5}Ge_{0.5}$ buffer

Absorption Coefficient (cm^{-1})



Peak Absorption Wavelength (μm)



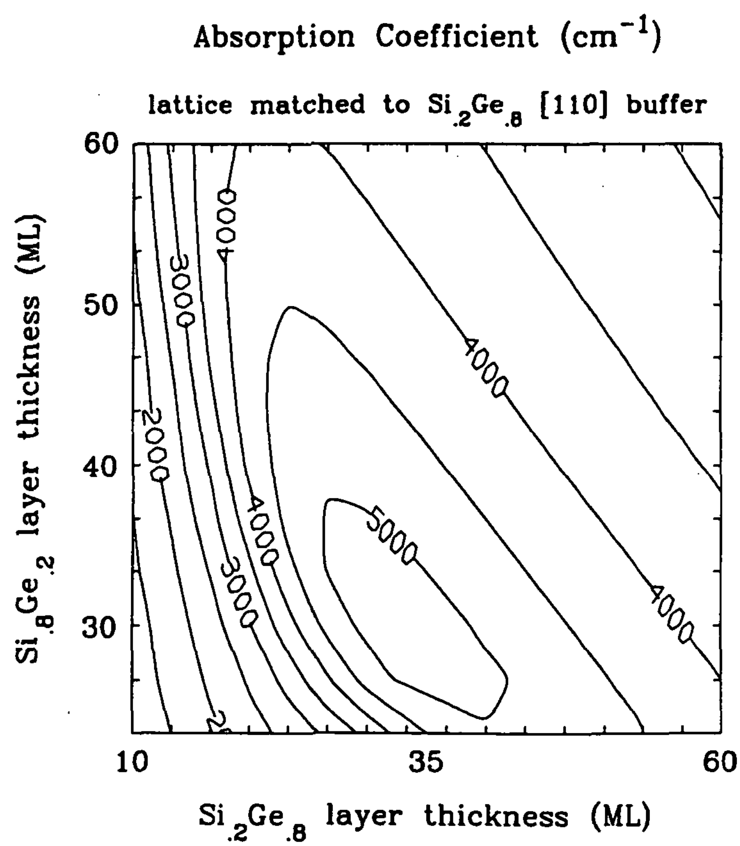
[110] direction
normal incidence
4-fold electrons

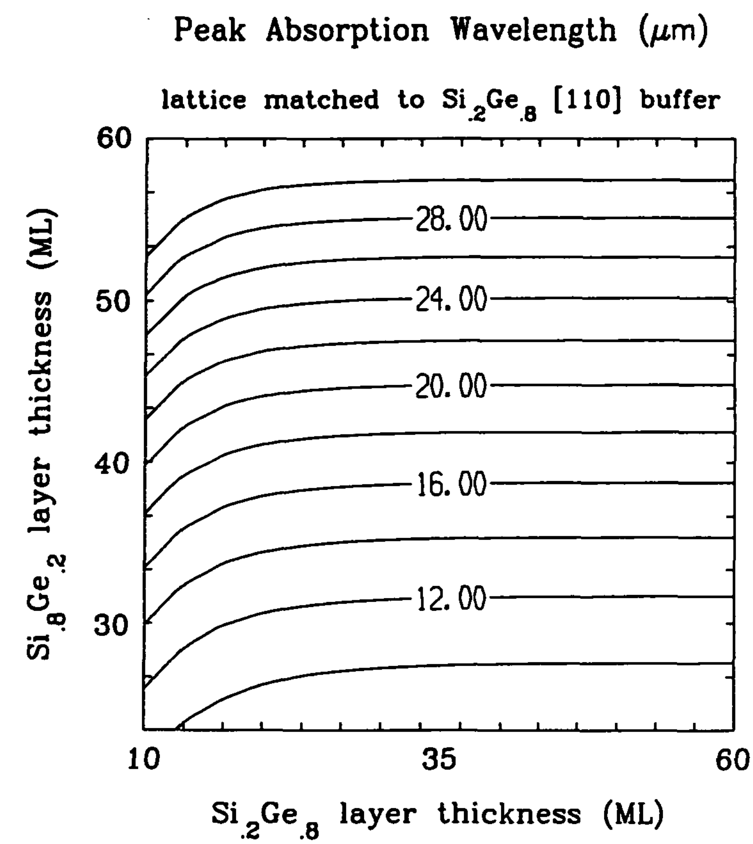
- effective masses: medium
  larger than [111]

- wavefunction confinement: medium
  better than [111]

- preferred azimuthal dependence
  for absorption in $[1\bar{1}0]$
  polarized light

- structures:
  - * barrier layer, Ge rich: $Si_{0.2}Ge_{0.8}$
  - * well layer, Si rich: $Si_{0.8}Ge_{0.2}$
  - * coherently strained to $Si_{0.2}Ge_{0.8}$ buffer





Other major issues

- Role of dislocations
- Excited state lifetime
- Intervalley scattering
- Responsivity, Detectivity

Conclusions

- Absorption of [100] Si/Ge superlattices is comparable to GaAs/AlGaAs (absorption coefficient $\approx 5000\ \text{cm}^{-1}$) for $10^{12}\ \text{cm}^{-2}$ doping.

- Absorption of [111], and [110] Si/Ge superlattices is superior to GaAs/AlGaAs since normal incidence can be detected

- Similar to extrinsic Si; Can vary absorption wavelength; Large absorption coefficients possible