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$_x$As/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$_x$As/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


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

\[ M_{op} = \left( \frac{e}{m_c} \right) \langle U_1 F_1 | \vec{A} \cdot \vec{P} | U_2 F_2 \rangle \]

- Interband Case: V → C

\[ M_{op} \sim \left( \frac{e}{m_c} \right) \langle U_C | \vec{A} \cdot \vec{P} | U_V \rangle \langle F_C | F_V \rangle \]

- Intersubband Case: C1 → C2

\[ M_{op} \sim \left( \frac{e}{m_c} \right) \langle F_{C1} | A_i \left( \frac{1}{m_*} \right) i_j P_j | F_{C2} \rangle \]

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 \(1/m_{yz}^* \) ≠ 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

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

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

- $\Gamma$ is the broadening due to lifetime $\approx (5 \text{ meV})$
- 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

Si [111] substrate

Si [110] substrate

CRITICAL THICKNESS
(Si parameters)

- Bean & People, 1986
- Van der Merwe, 1963
- Matthews & Blakeslee, 1974

THICKNESS (Å)

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
[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

Absorption Coefficient (cm$^{-1}$)
lattice matched to Si$_{0.7}$Ge$_{0.3}$ [100] buffer
Peak Absorption Wavelength (\(\mu m\))
lattice matched to Si\(_{7.0}\)Ge\(_{3.0}\) [100] 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$^{-1}$)

lattice matched to Si$_5$Ge$_5$ [111] buffer

Peak Absorption Wavelength (μm)

lattice matched to Si$_5$Ge$_5$ [111] buffer
[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 [110]
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

Absorption Coefficient (cm$^{-1}$)
lattice matched to Si$_{2.5}$Ge$_{0.5}$ [110] 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.