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Modeling of intersubband transitions in quantum well infrared photodetectors with complex well and barrier structure

Liu Wei and Zhang Dao Hua

EEE School, Nanyang Technological University

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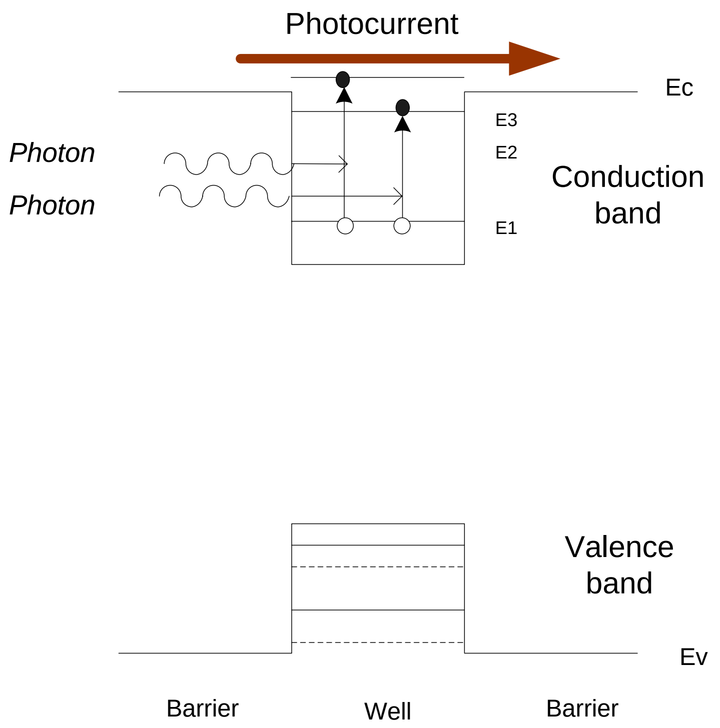
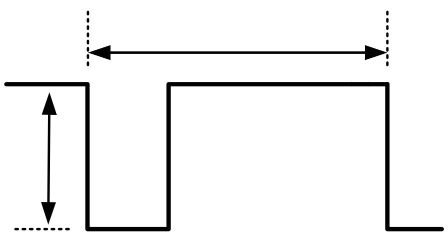
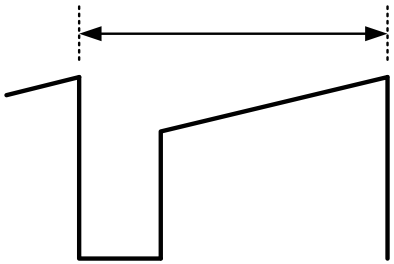
Fundamentals of quantum-well infrared photodetector (QWIP)

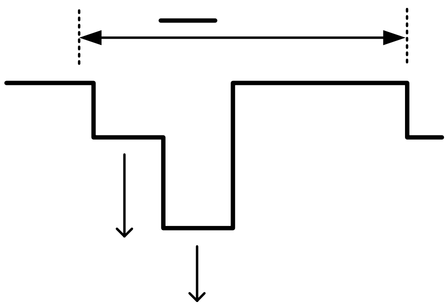


QWIPs operate by photoexcitation of electrons between ground and excited state subbands of multi-quantum wells (MQWs) The bandgap discontinuity of two materials creates quantized subbands in the potential wells associated with conduction bands or valence bands. The structure parameters are designed so that the photo-excited carriers can escape from the potential wells and be collected as photocurrent.

QWIPs designed with different well and barrier structures



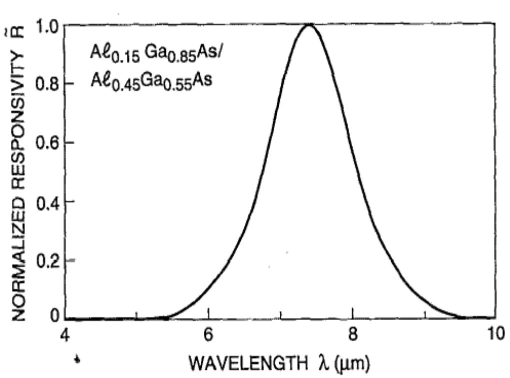


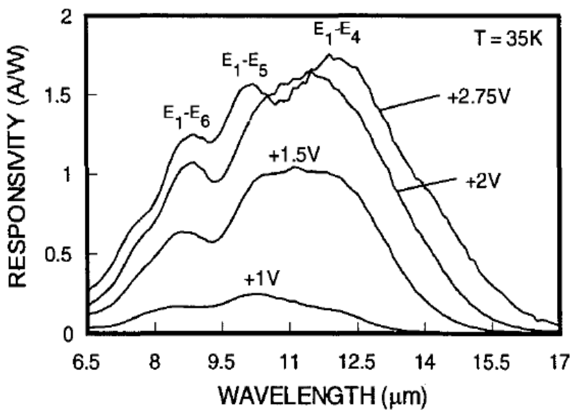


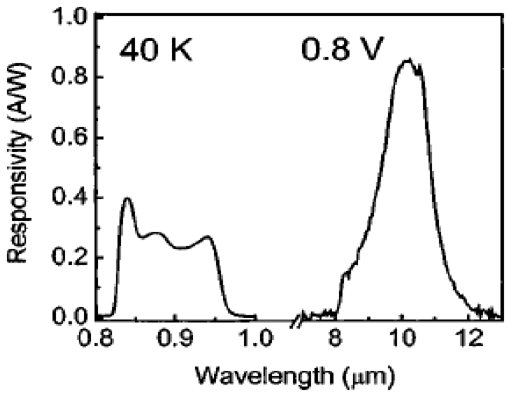
Ordinary rectangular QW

QW with linear-graded barrier for voltage-tunable broad-band photodetection

Multiply Step QW







Theoretical Model

8-band k·p Hamiltonian

$$
\mathbf{H}_k = \begin{bmatrix}
C & 0 & -pk_+ & \sqrt{\frac{2}{3}}pk_z & \frac{1}{\sqrt{3}}pk_- & 0 & \frac{1}{\sqrt{3}}pk_z & \sqrt{\frac{2}{3}}pk_- \\
\cdots & C & 0 & \frac{-1}{\sqrt{3}}pk_+ & \sqrt{\frac{2}{3}}pk_z & pk_- & \sqrt{\frac{2}{3}}pk_+ & \frac{-1}{\sqrt{3}}pk_z \\
\cdots & \cdots & F & H & I & 0 & \frac{H}{\sqrt{2}} & \sqrt{2}I \\
\cdots & \cdots & \cdots & G & 0 & I & \frac{1}{\sqrt{2}}(G-F) & -\sqrt{\frac{3}{2}}H \\
\cdots & \cdots & \cdots & \cdots & G & -H & -\sqrt{\frac{3}{2}}H^* & \frac{-1}{\sqrt{2}}(G-F) \\
\cdots & \cdots & \cdots & \cdots & \cdots & F & -\sqrt{2}I^* & \frac{H^*}{\sqrt{2}} \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \frac{F+G}{2}-\Delta & 0 \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \frac{F+G}{2}-\Delta
\end{bmatrix}
$$

$$k_+ = (k_x + ik_y)/\sqrt{2} \qquad k_- = (k_x - ik_y)/\sqrt{2} \qquad C = E_g + \frac{\hbar^2 k^2}{2m_0}\left[\frac{1}{m_e^*} - \frac{E_P}{3}\left(\frac{2}{E_g} + \frac{1}{E_g+\Delta}\right)\right]$$

$$F = Ak^2 + \frac{B}{2}(k^2 - 3k_z^2) \qquad G = Ak^2 - \frac{B}{2}(k^2 - 3k_z^2) \qquad H = -Dk_z(k_x - ik_y)$$

$$I = -\frac{\sqrt{3}}{2}B(k_x^2 - k_y^2) + iDk_xk_y \qquad A = -\frac{\hbar^2\gamma_1}{2m_0} \qquad B = -\frac{\hbar^2\gamma_2}{m_0} \qquad D = -\sqrt{3}\frac{\hbar^2\gamma_3}{m_0}$$

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Theoretical Model

Wave function and Fourier Expansion

$$\Psi(r)=\sum_{j=1}^{8}F_j(r)u_j(r)=\sum_{j=1}^{8}\exp(ik_t\rho)\varphi_j(z)u_j(r)$$

$$F_j(r)=\exp[i(k_x x+k_y y)]\sum_m a_{j,m}\frac{1}{\sqrt{L}}\exp\left[i\left(k_z+m\cdot\frac{2\pi}{L}\right)\cdot z\right]$$

Coupled differential equations

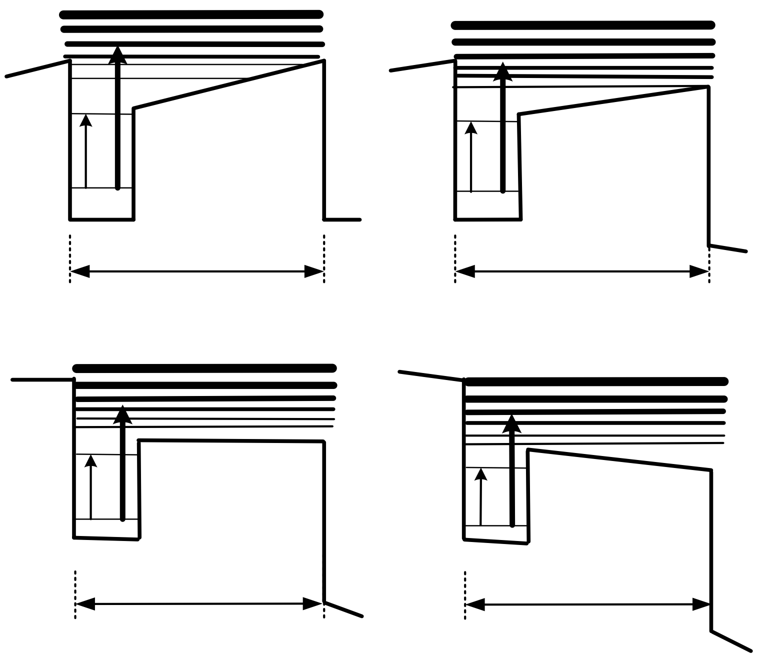
$$\sum_{j'=1}^{8}\left(H_{j,j'}+U(z)\delta_{j,j'}\right)F_{j'}(r)=EF_j(r) \Longrightarrow \sum_{j',m'}H_{j,j'}(m,m')a_{j',m'}=Ea_{j,m} \quad j,j'=1,\ldots,8$$

$$H_{j,j'}(m,m')=\int_{-L/2}^{L/2}\phi_m^*(z)\left[H_{j,j'}+\delta_{j,j'}U(z)\right]\phi_{m'}(z)dz$$
$$=\langle m|H_{j,j'}+\delta_{j,j'}U(z)|m'\rangle$$

$$U(z)=V_0+V_s+q\varepsilon z$$

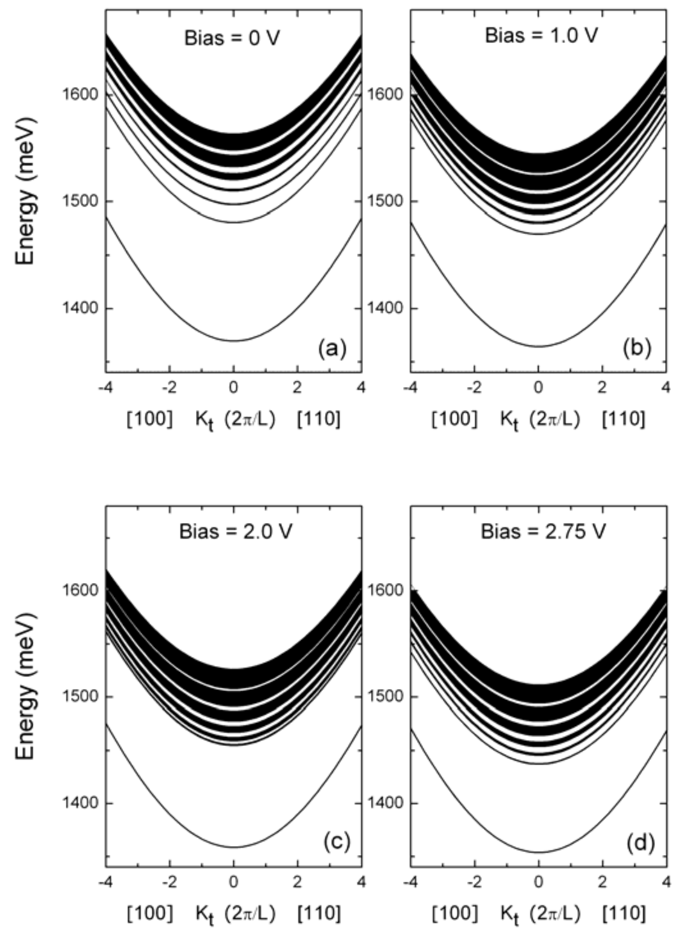
V_0 : the QW potential induced by the band discontinuity of barrier and well,
V_s *:* the potential change induced by strain
q ε z : the potential change induced by applied bias

Calculation results



Schematical conduction band profiles under different biases

$In_{0.26}Ga_{0.74}As/Al_xGa_{1-x}As$ (x = 0.018-0.09) QWIP with linear-graded barrier (LGB)



Calculated subband dispersions under different biases

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Calculation results

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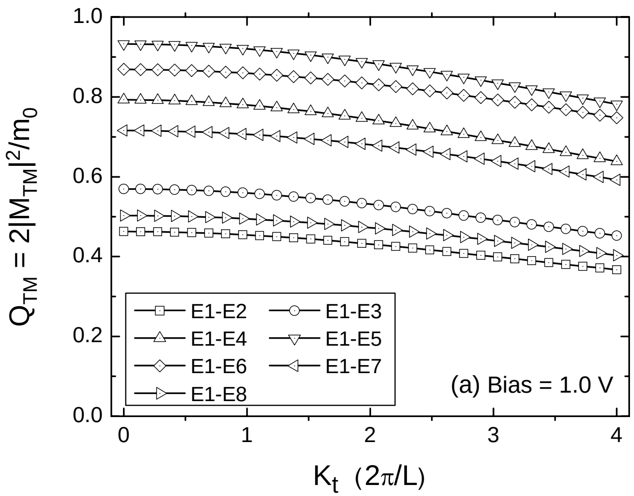
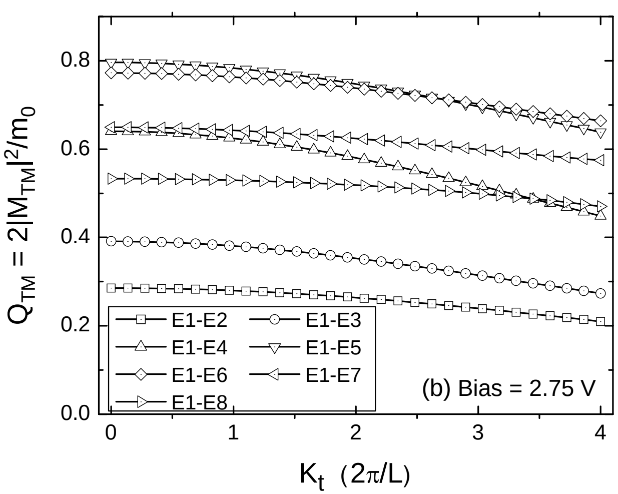
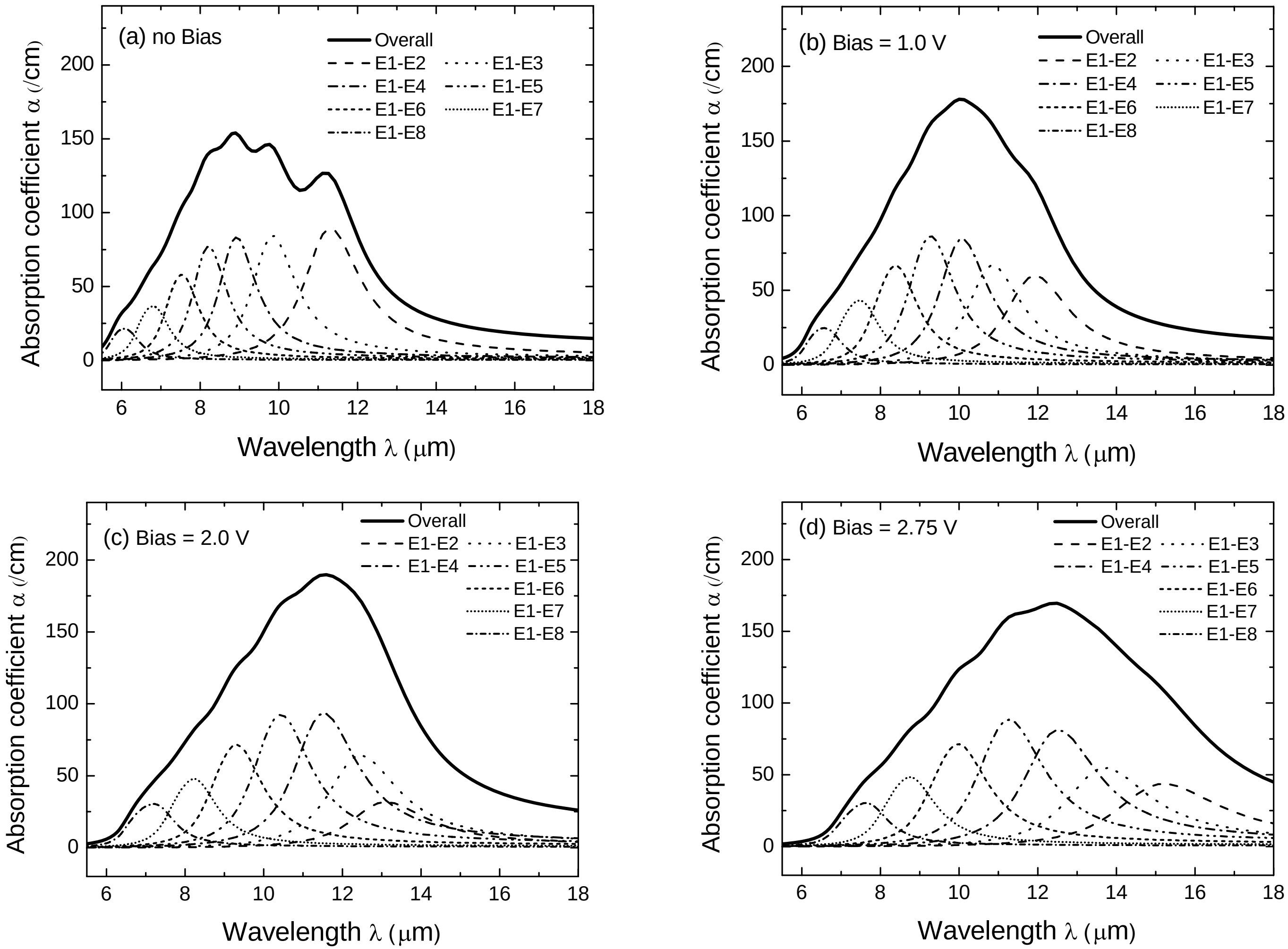




Calculated squared optical transition matrix elements for TM polarization

Calculation results



Calculated optical absorption coefficients as a function of optical wavelength of different intersubband transitions

Conclusion

- the higher excited states appear to be minibands whose width increases with the order of the state due to the relaxation of quantum confinement.
- All the excited states go downwards evidently with increasing bias due to the lowering of LGB (linear-graded barrier)
- all the transitions have considerable rates. The transition rates from the ground state E1 to higher excited states, i.e. E4, E5 and E6, are relatively large, unlike the situation in ordinary symmetrical rectangular QWs
- At 2.75 V, the spectral FWHM increases to about 7.0 μm (8.9-15.9 μm), and the peak absorption wavelength also red-shifts to 12.3 μm. The ratio of FWHM to the peak wavelength is about 56 %.
- Excellent consistence with the experimental observation

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Thank you!