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School of Electrical and Electronic Engineering

Studying of intra-band and inter-band transitions in InSbN/InSb quantum well using 10-band k·p model

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Recent progress – InSbN material

- The growth and characterization of $InSb_{1-x}N_x$ was first reported in 2000 [1]
- The introduction of dilute nitrogen into the binary InSb is to reduce the bandgap based on band anti-crossing (BAC) effect [1, 2]. Negative bad gap observed in $InSb_{1-x}N_x$ alloys have also been reported [3]
- The room temperature LEDs comprising an $InSb_{0.945}N_{0.055}$/InSb superlattice structure peaked at 10.5 μm has been realized[4]
- The Auger recombination rate in $InSb_{1-x}N_x$ is only about one third of that of the equivalent band gap mercury cadmium telluride (MCT) [5]

[1] A. D. Johnson, R. H. Bennett, J. Newey, et al.,"InNxSb1-x light emitting diodes grown by MBE," *Mater. Res. Soc. Symp. Proc. 2000*, 607:23-8

[2] B. N. Murdin, A. R. Adams, P. Murzyn, et al., "Band anticrossingin dilute InN_xSb_{1-x}," *Appl. Phys. Lett.*, vol. 81, no. 2, pp. 256-258, 2005

[3] T. D. Veal, I. Mahboob, and C. F. McConville, "Negative Band Gaps in Dilute InN_xSb_{1-x} Alloys," *Phys. Rev. Lett.*, vol. 92, no. 13, 136801, 2004

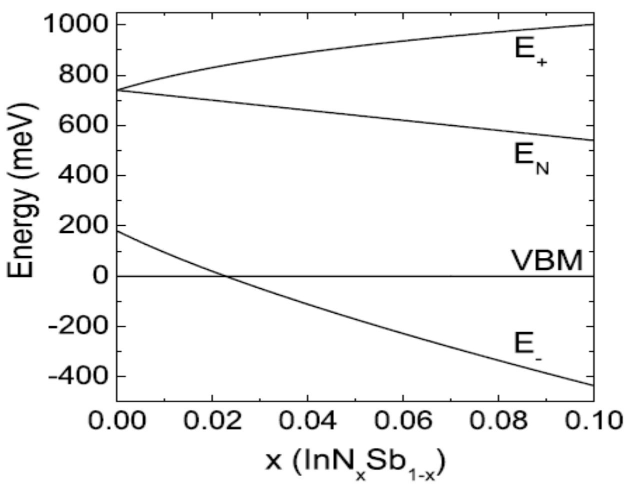
[4] T. Ashley, T. M. Burke, G. J. Pryce, et al., "InSb1–xNx growth and devices," Solid-State Electronics, Vol. 47, pp. 387-394, 2003

[5] B. N. Murdin, M. Kamal-saadi, A. Lindsay, et al., "Auger recombination in long-wavelength infrared InNxSb1–x alloys", *Appl. Phys. Lett.*, vol. 78, no. 11, pp. 1568-1570, 2001.

$InSb_{1-x}N_x$/InSb QW for IR detection

- Because of the band anti-crossing (BAC) effect that generates E+ and E- bands in InSbN, the InSbN/InSb system appear to be an equivalent QW structure since the E- state is markedly below the InSb conduction band edge. In this article, we aim to present an effective theoretical analysis on the InSbN/InSb based structures

- To exploit the possibility of $InSb_{1-x}N_x$ /InSb QW for long-wavelength infared photodetection based on inter-band and intra-band transitions



Calculated band dispersion with the N content using BAC model

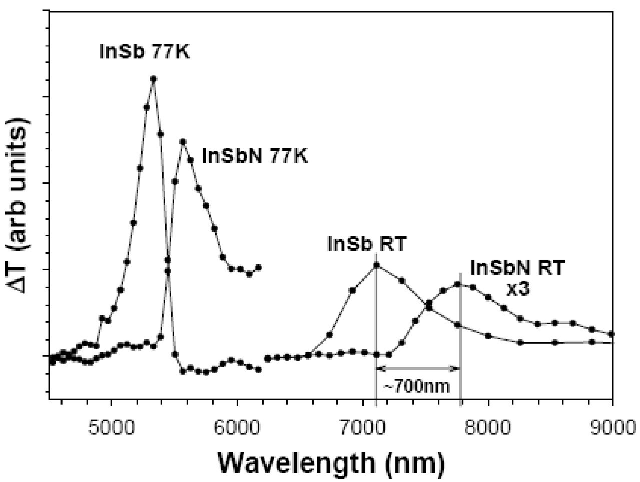


Photo-modulated transmission results on InSbN and InSb

Theoretical method

10-band k·p Hamiltonian

$$\mathbf{H} = \begin{bmatrix} \mathbf{H}_{p\bar{s}} & \mathbf{H}^{*}_{p\bar{s}-N} \\ (8\times 8) & (8\times 2) \\ \mathbf{H}_{p\bar{s}-N} & \mathbf{H}_{N} \\ (2\times 8) & (2\times 2) \end{bmatrix}$$

$\mathbf{H}_{p\bar{s}}$ **— the conventional 10-band k·p Hamiltonian** $\mathbf{H}_{N}$ **— the N band Hamiltonian**

$\mathbf{H}_{p\bar{s}-N}$ **— consists the coupling terms connecting conduction band and valance band with N states**

$$\mathbf{H}_{N} = \begin{bmatrix} E_{N0} + \alpha_N k^2 & 0 \\ 0 & E_{N0} + \alpha_N k^2 \end{bmatrix} \qquad \mathbf{H}_{p\bar{s}-N} = \begin{bmatrix} V_{NC} & 0 & -\sqrt{3}T_{N+} & \sqrt{2}Q_N & -T_{N-} & 0 & -Q_N & -\sqrt{2}T_{N-} \\ 0 & V_{NC} & 0 & T_{N+} & \sqrt{2}Q_N & -\sqrt{3}T_{N-} & \sqrt{2}T_{N+} & -Q_N \end{bmatrix}$$

The total wave function is $\Psi(r) = \sum_{j=1}^{10} F_j(r)u_j(r) = \sum_{j=1}^{10} \exp(ik_t\rho)\varphi_j(z)u_j(r)$

The envelope functions are then expanded to a discrete Fourier series:

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

Calculated results

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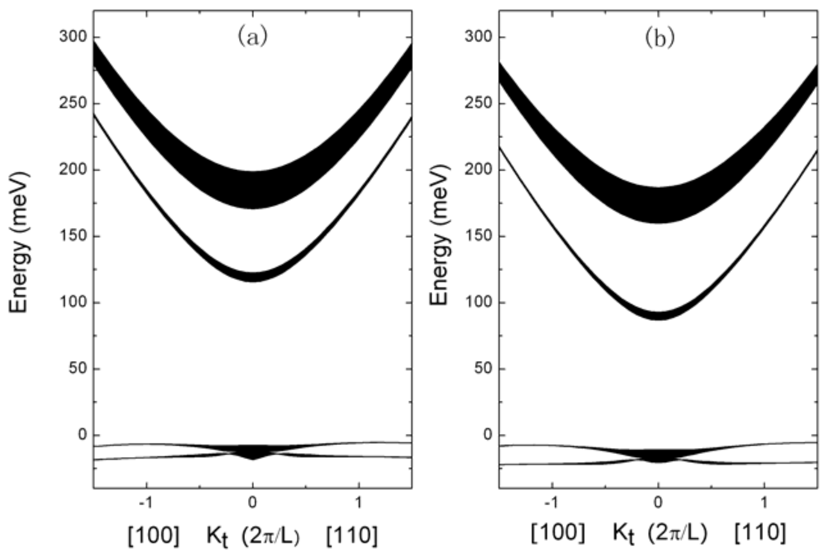
Subband energy dispersions



(a) $InSb_{0.99}N_{0.01}$/InSb MQW and (b) $InSb_{0.985}N_{0.015}$/InSb MQW

InSbN well width is 14 nm and InSb barrier is 25 nm

The lowest two subbands in conduction (E1, E2) and valence band (HH1, LH1) are displayed

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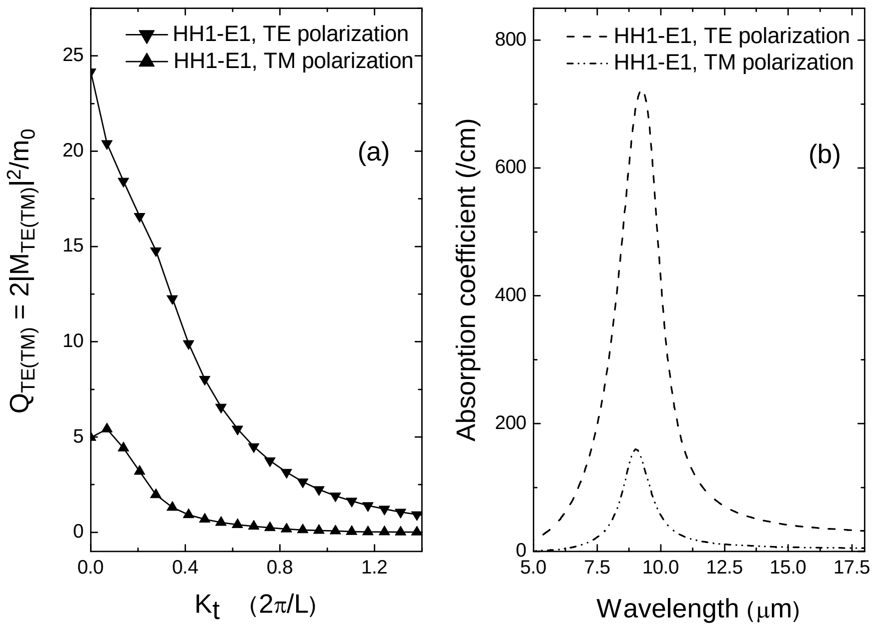
Calculated results

Inter-band transitions



Calculated (a) squared optical transition matrix elements vs plane wave vector k_t and (b) absorption coefficients vs. optical wavelength of E1-HH1 transition for TE and TM polarizations

$InSb_{0.99}N_{0.01}/InSb$ MQW

Calculated results

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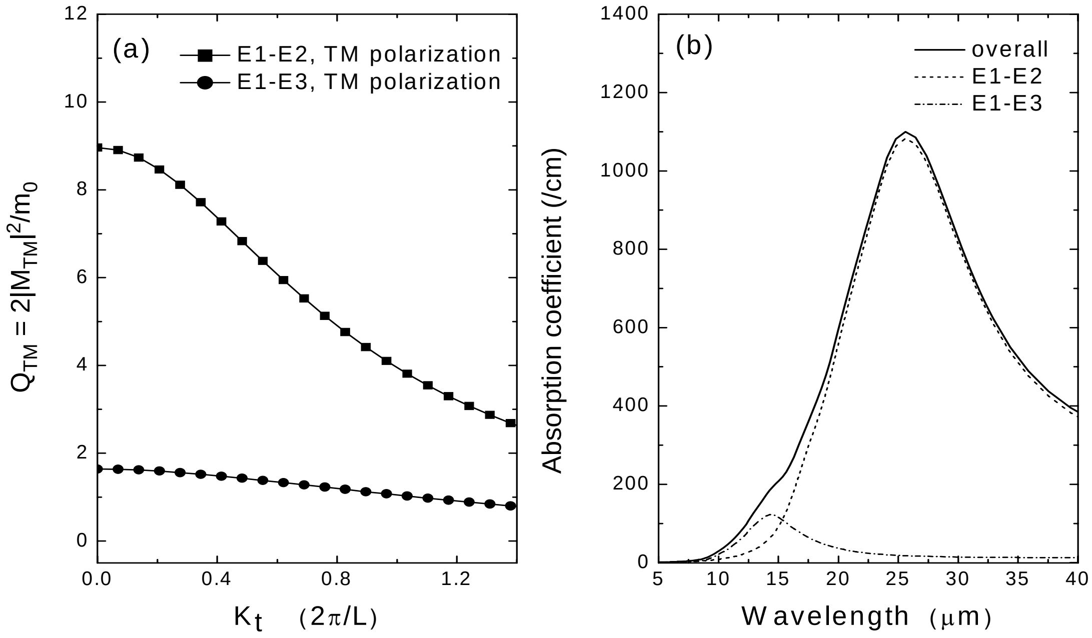
Intra-band (inter-conduction subband) transitions



Calculated (a) squared optical transition matrix elements vs. plane wave vector k_t and (b) absorption coefficients vs. optical wavelength of intra-conduction band E1-E2 and E1-E3 transitions for TM polarization

$InSb_{0.99}N_{0.01}/InSb$ MQW

Conclusion

- The squared optical transition matrix elements of intra-band transitions show very large amplitude. The peak value is about 9, which is over one third of the interband one (about 24). It's 5-10 times greater than that of usual GaAs/AlGaAs systems (about 0.5-2).

  This is due to the very narrow bandgap of InSb(N) material that strengths the valence-conduction state coupling effect and hence improves inter-conduction subband transition rates.

- The interband transition shows absorption peak at 9.25 μm. The intraband transition shows absorption peak at 25.8 μm. It's indicated that the InSbN/InSb system is potentially advantageous for photodetection at various infrared wavelength band.

Thank you!