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Simulations of Resonant Intraband and Interband Tunneling Spin Filters

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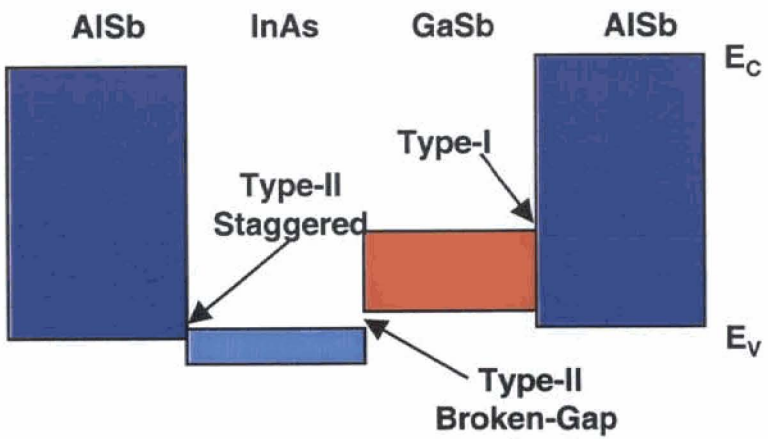
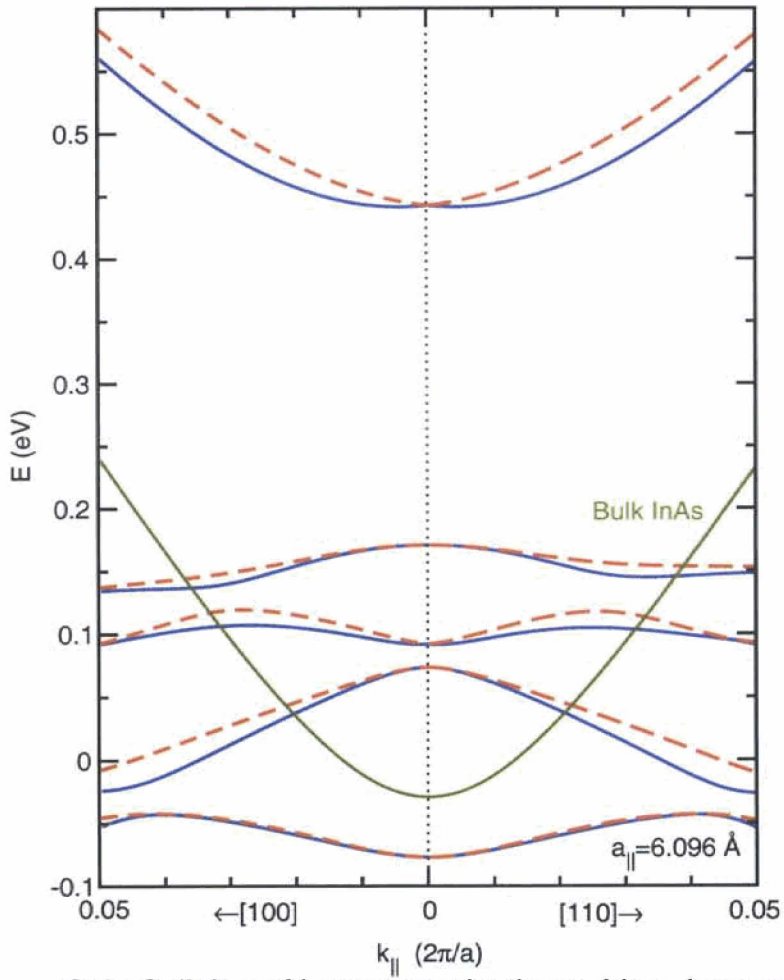
Rashba Spin Splitting

- Spin splitting due to spin-orbit interaction in asymmetric heterostructures (removal of Kramers degeneracy).
- Splitting is k-dependent:
  - Linear for small k: $\Delta E = 2\alpha|k|$
  - Vanishes at zone center.
- Conventional III-V semiconductors heterostructures.
- Zero-magnetic-field spin splitting.

AlSb/InAs/GaSb asymmetric superlattice

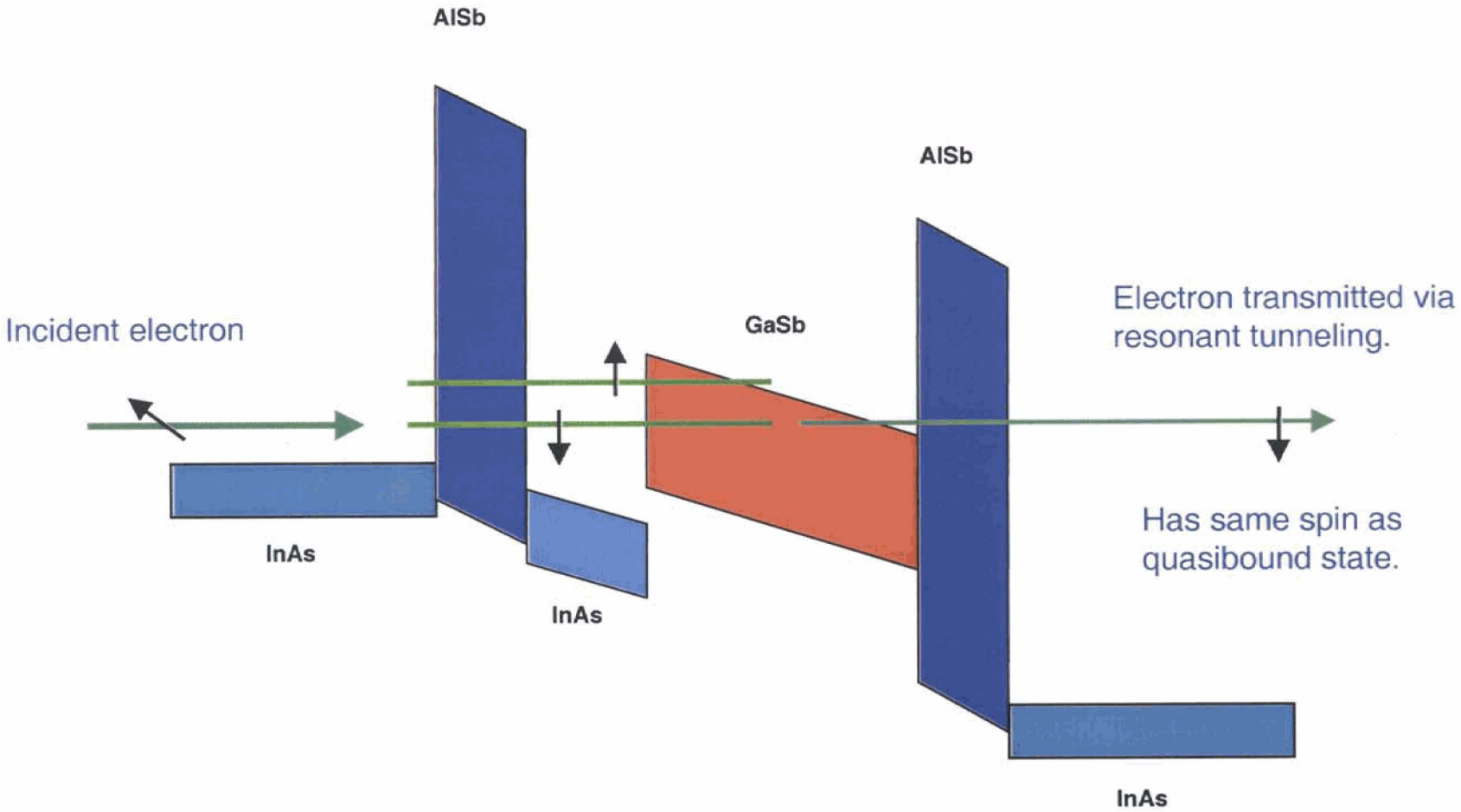


(8,18,12)-InAs/GaSb/AlSb Superlattice

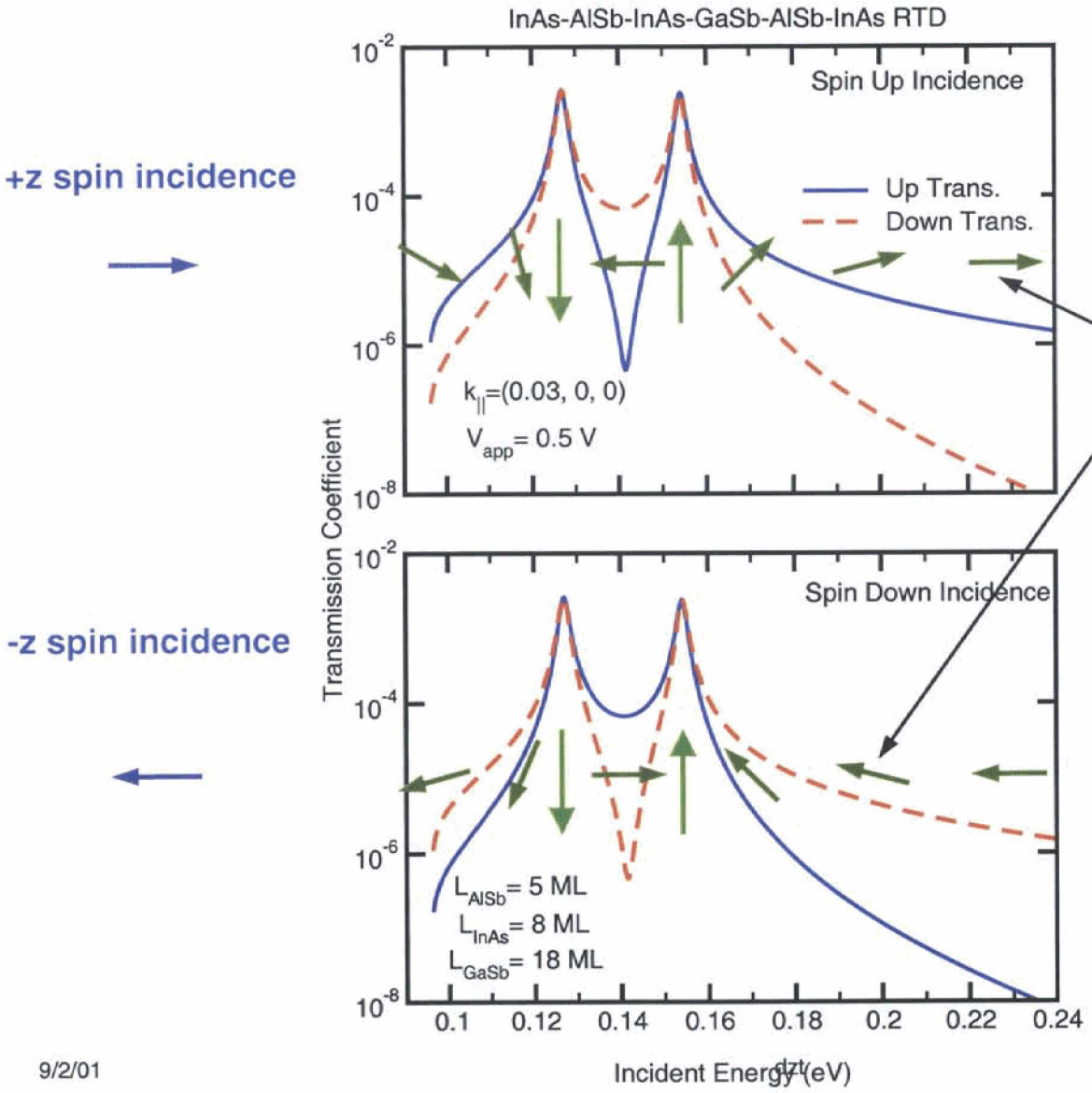


Spin Splitting of lowest conduction subband exceeds 20 meV at $k_{||}$=0.05 (2π/a). No external biasing.

Rashba Effect
Resonant Tunneling Spin Polarizer



Spin Polarization by Resonant Tunneling



+z spin incidence

-z spin incidence

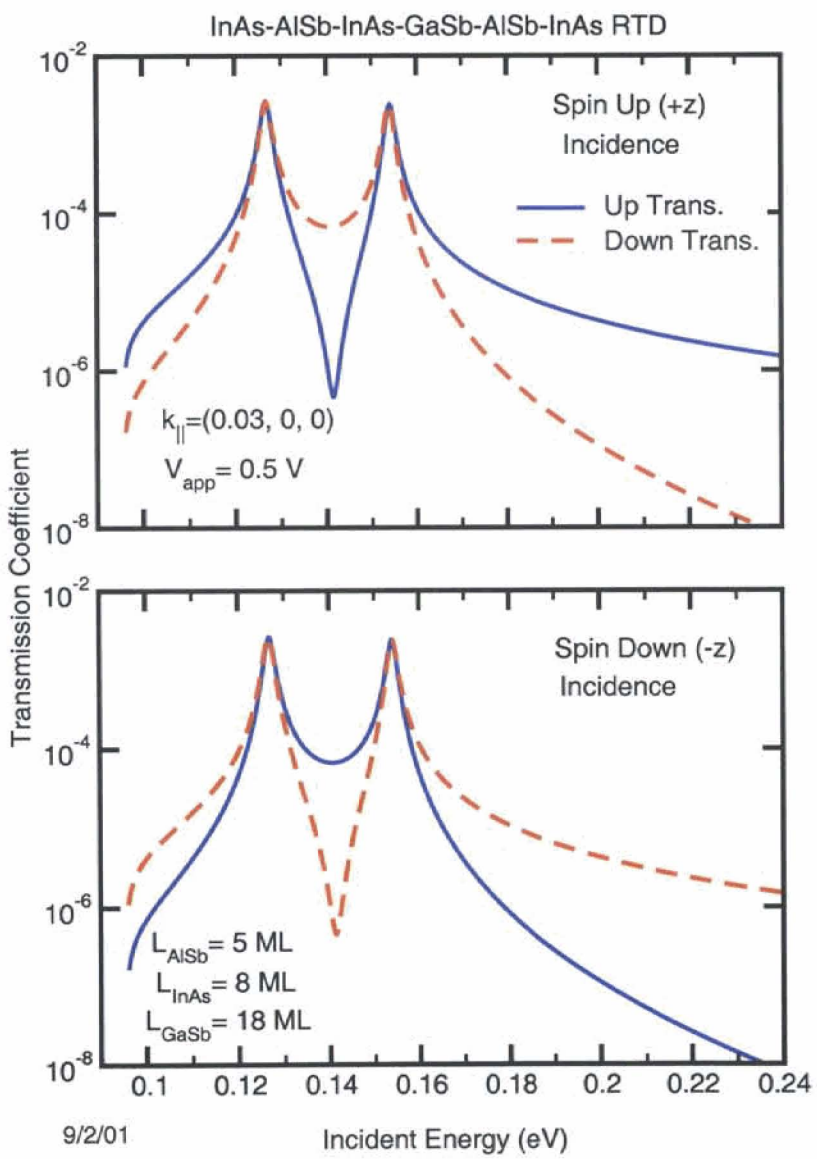
y

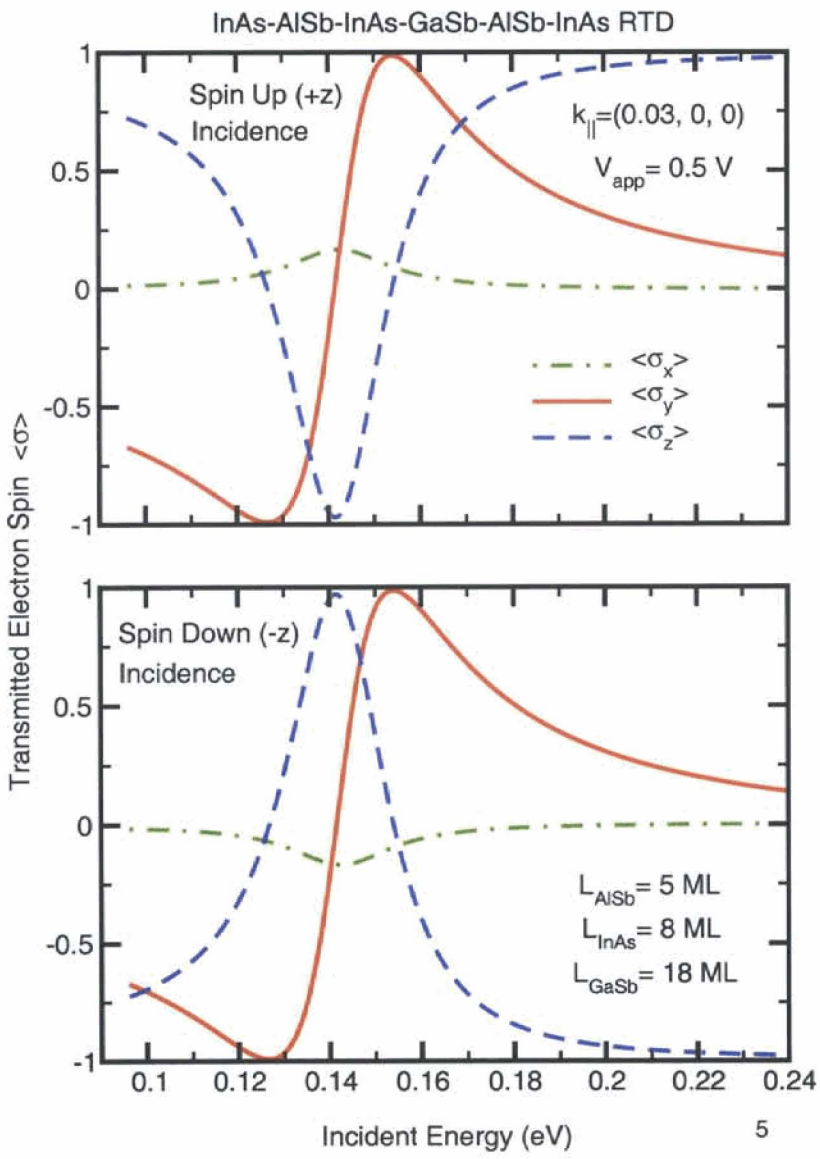
z

Transmitted state spin direction.

- Transmitted electrons retain incidence spin at energies above or below the resonances.
- In between the resonances, the spin of the transmitted electron is flipped from the incident spin.
- On resonance, transmitted states are spins polarized by the quasibound states.

Spin-Dependent Transmission Intraband Resonant Tunneling Structure



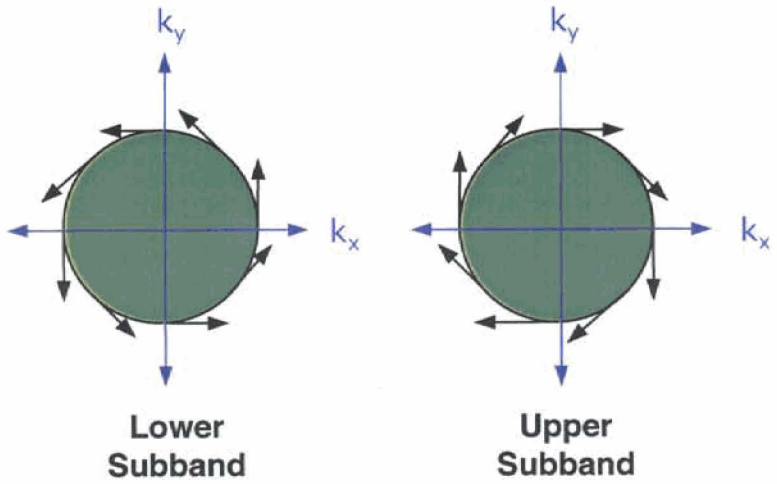


Challenges Presented by Spin Directions of Quantized States

Spin-Orbit Interaction:

$$H_{so} = C\ \sigma \cdot \nabla V \times \mathbf{p} = \sigma \cdot \mathbf{B}_{eff}$$

- $\mathbf{B}_{eff} \perp \nabla V$:
  - Spin in the plane of quantum well
- $\mathbf{B}_{eff} \perp \mathbf{p}$:
  - Spin perpendicular to the $\mathbf{k}_{||}$ vector
- $|\mathbf{B}_{eff}| \propto |\mathbf{p}|$:
  - Spin splitting vanishes for $k_{||} = 0$.



Calculated spin directions for quantum well states lying on circles of constant in-plane *k* for the lowest two spin split conduction subbands.

- **Opposite spins for**
  - two subbands at the same $\mathbf{k}_{||}$.
  - $+\mathbf{k}_{||}$ and $-\mathbf{k}_{||}$ states in the same subband
- **No net spin !**

JPL

Strategies

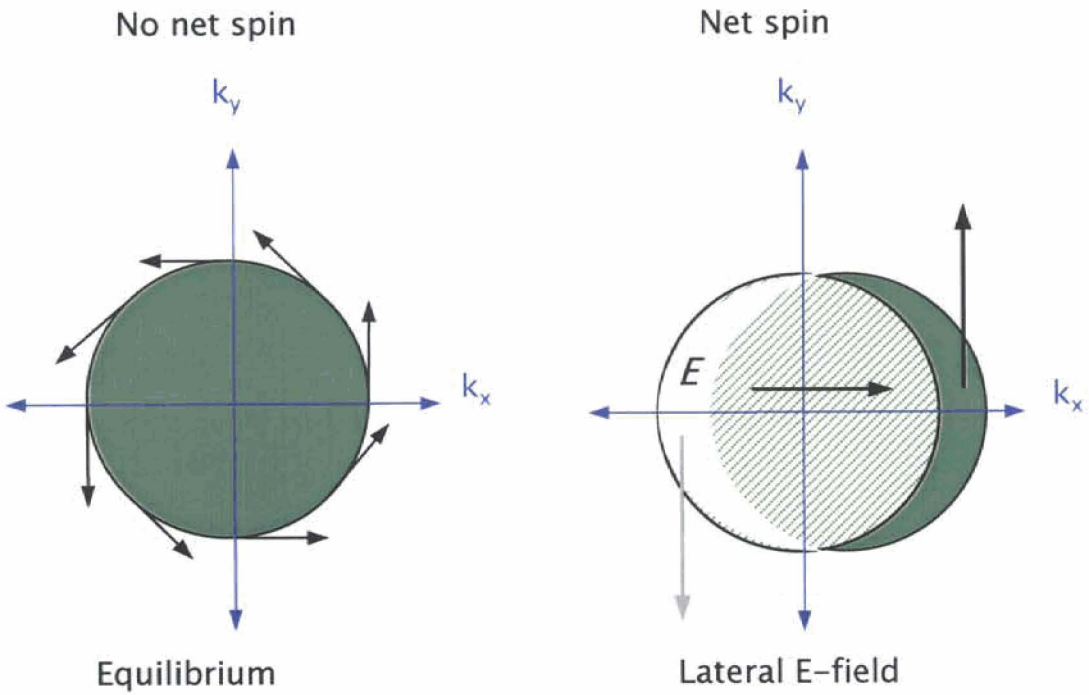
To polarize spins using the Rashba effect in RTD, we must have energy and momentum selectivity:

- Opposite spins for two subbands at the same $\mathbf{k}_{||}$:
  - Optimize spin splitting (InAs/GaSb/AlSb).
  - Resonant tunneling for energy selectivity.

- Opposite spins for $+\mathbf{k}_{||}$ and $-\mathbf{k}_{||}$ states in the same subband :
  - Use a lateral E-field to create an anisotropy in the electron lateral momentum distribution.

- Spin splitting vanishes for $k_{||} = 0$:
  - Zone center region relatively small, relatively unimportant. (???)
  - Addressed by new device concept.

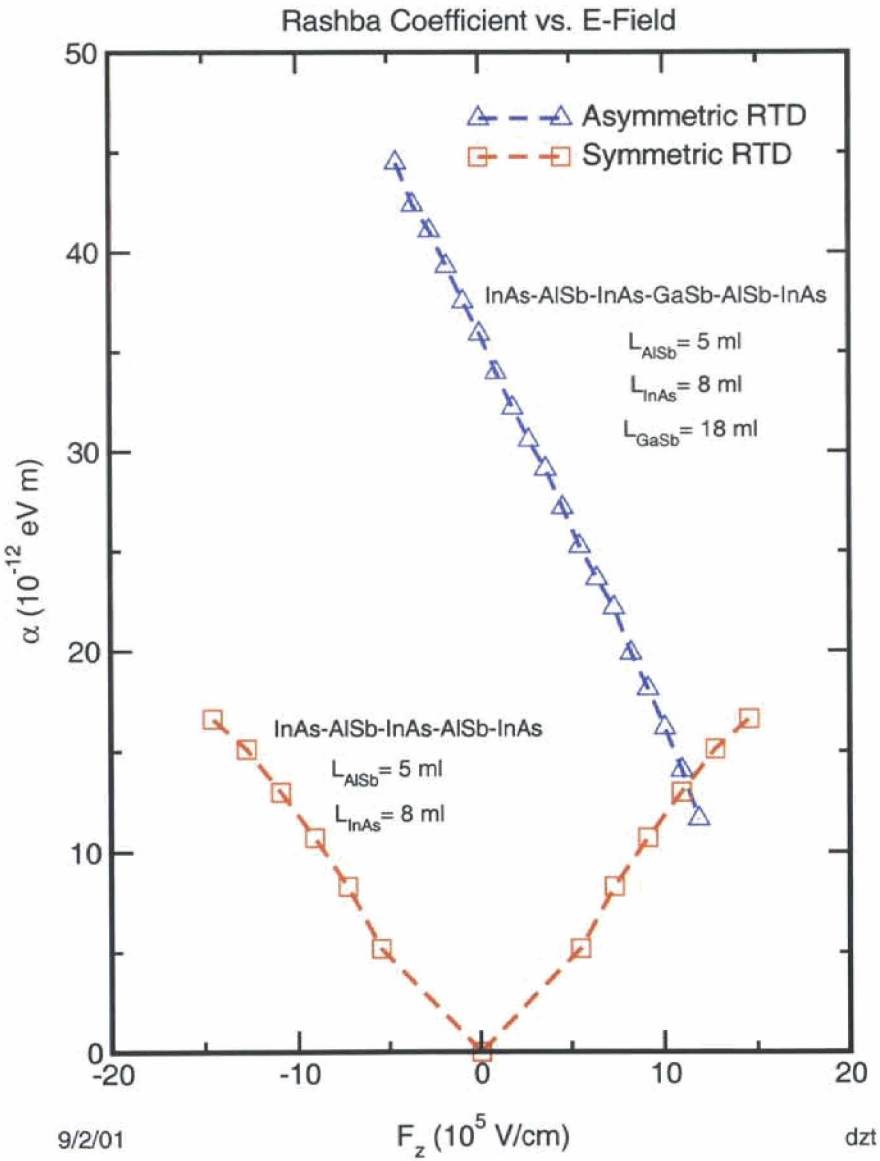
Creating Anisotropy in Lateral Momentum Distribution



The application of an in-plane E-field displaces the Fermi surface, resulting in a net spin for the subband.

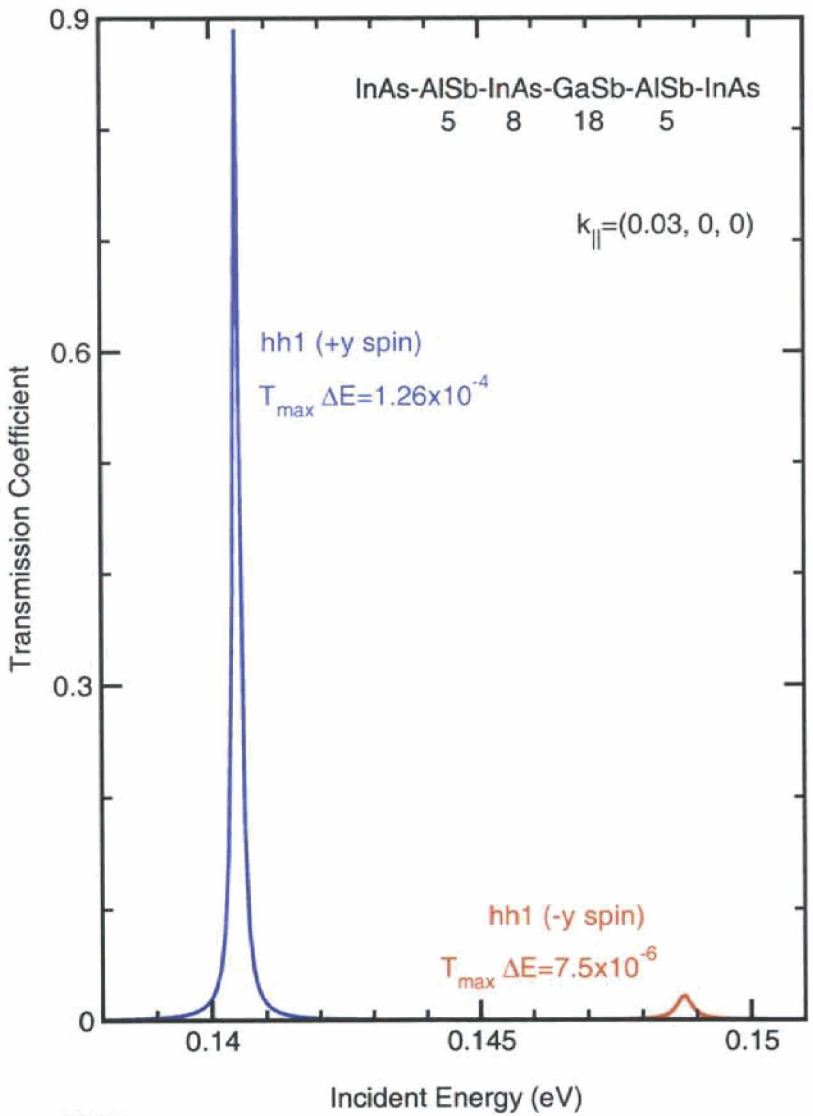
- Apply lateral E-field to create anisotropy in lateral momentum distribution of electrons undergoing resonant tunneling.
- Theoretical prediction of polarization in tunneling current of an asymmetric InAs/AlAs/GaAs RTD. [A. Voskoboynikov, S.S. Lin, and C.P. Lee. *J. Appl. Phys.* **87**, 387 (2000)].
- InAs/GaSb/AlSb offers possibility for larger spin splitting.

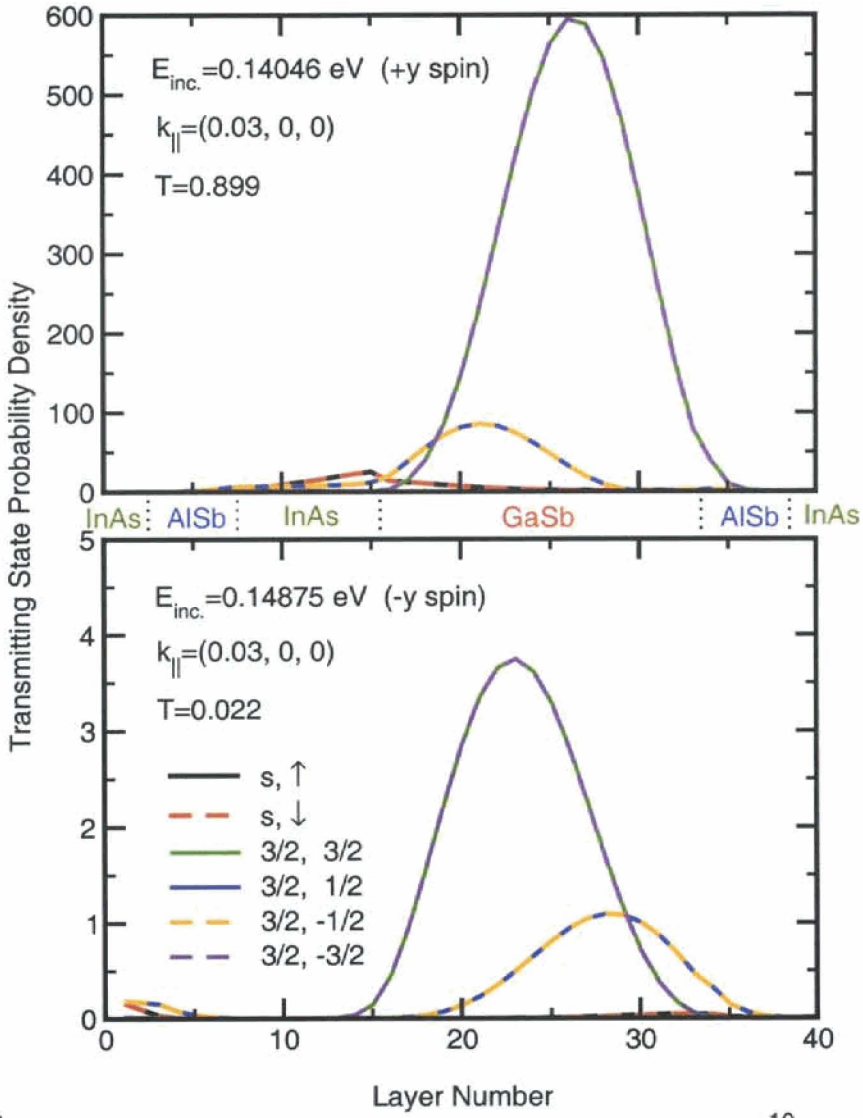
Dependence of Spin Splitting on Applied Bias



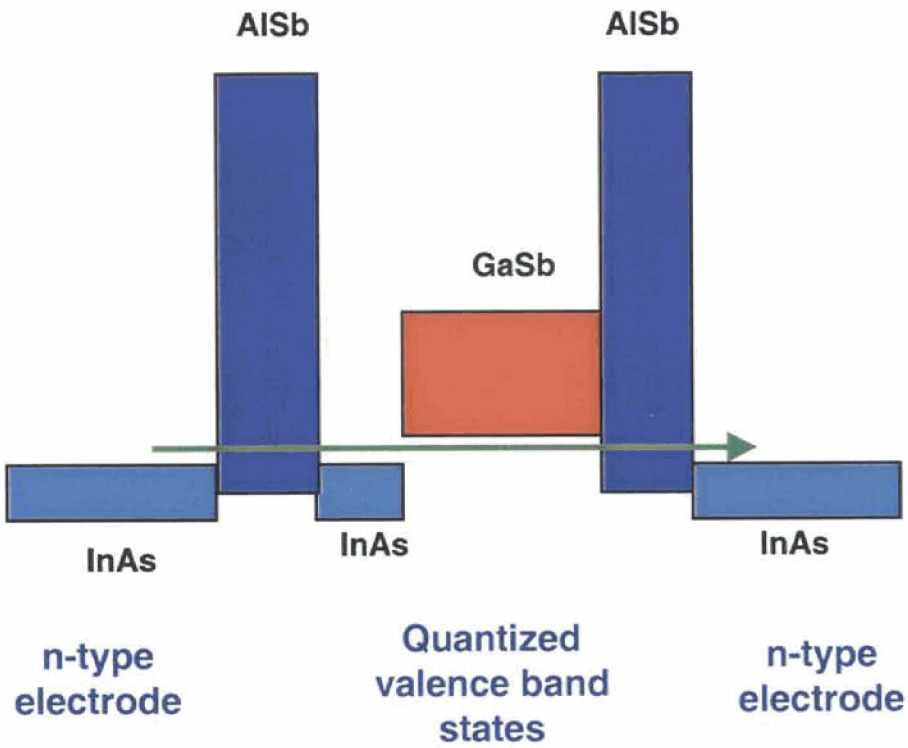
- Compute Rashba coefficient as function of applied (transverse) bias, using spin splitting in resonant transmission spectra.
- Intraband (CB-CB-CB) resonant tunneling regime.
- Symmetric RTD
  - No spin splitting at zero bias.
- Asymmetric RTD
  - Non-zero spin splitting at zero bias.
  - Can optimize Rashba coefficient by choosing the proper polarity.

Transmitting State Wave Functions Interband Resonant Tunneling Structure





Resonant Interband Tunneling Diode



- J. R. Söderström, David H. Chow, T. C. McGill (1989).
- Large peak-to-valley ratio. Wide valley. Low-bias operation.
- Extensive simulation experience.
- For spin-splitting, insert InAs layer in well region to create inversion asymmetry.
- Asymmetric resonant interband tunneling diode (**a-RITD**).

Spin-Dependent Transmission Properties
Intraband vs. Interband Resonant Tunneling

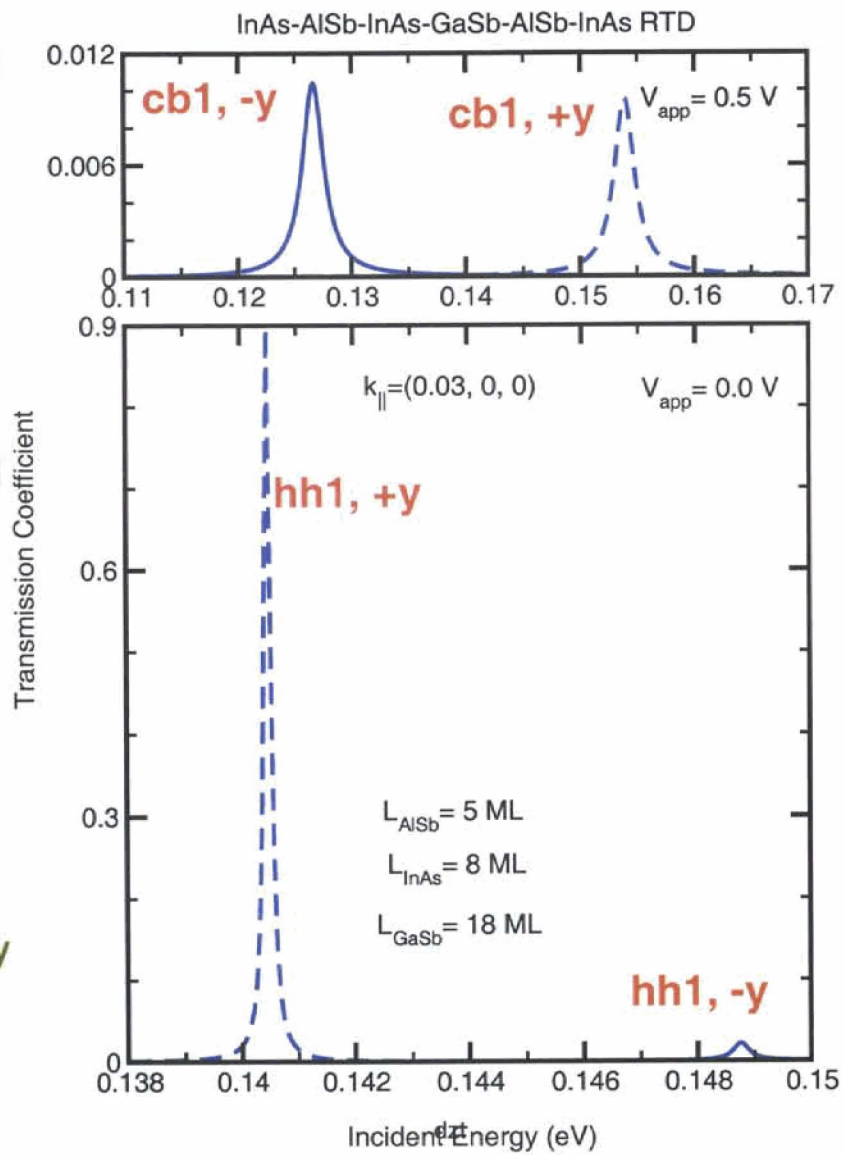
Resonant Intraband Tunneling:

cb-cb1-cb

Resonant Interband Tunneling:

cb-hh1-cb

Incidence spin: +y or -y

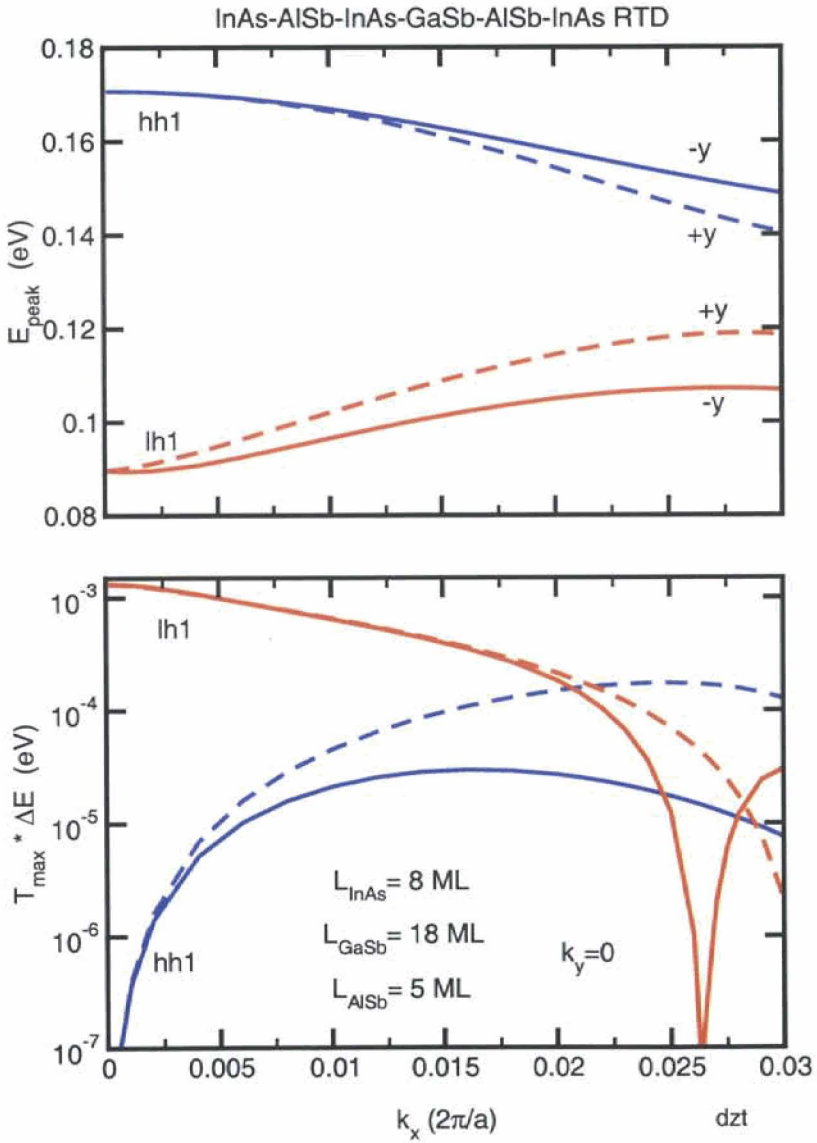


Comparable transmission thru two spin-split cb1 channels.

Very large difference in transmission between spin-split hh1 channels !

(T_{max} ΔE ratio = 16.8)

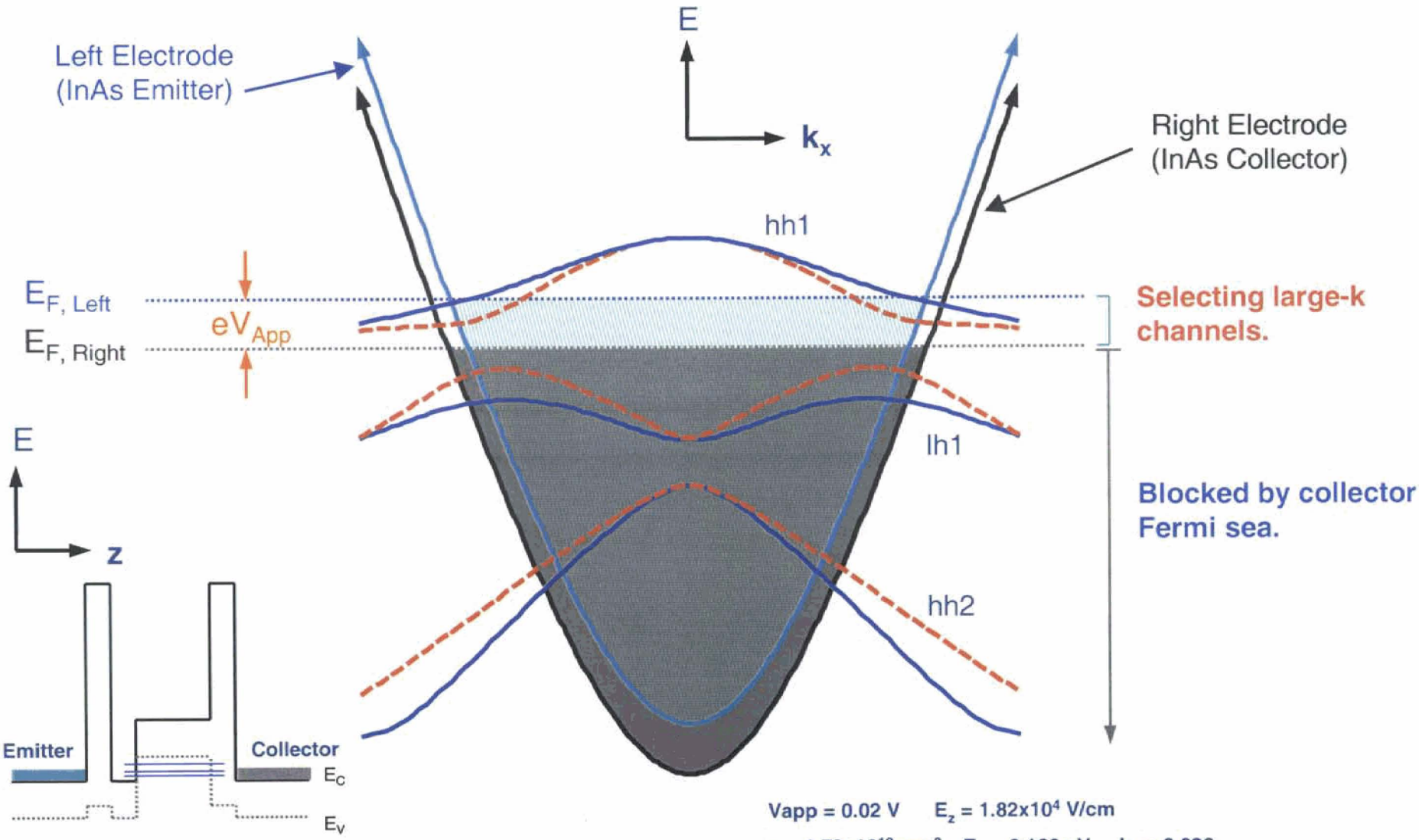
k-Dependent Transmission Properties of Interband Resonant Tunneling Structure



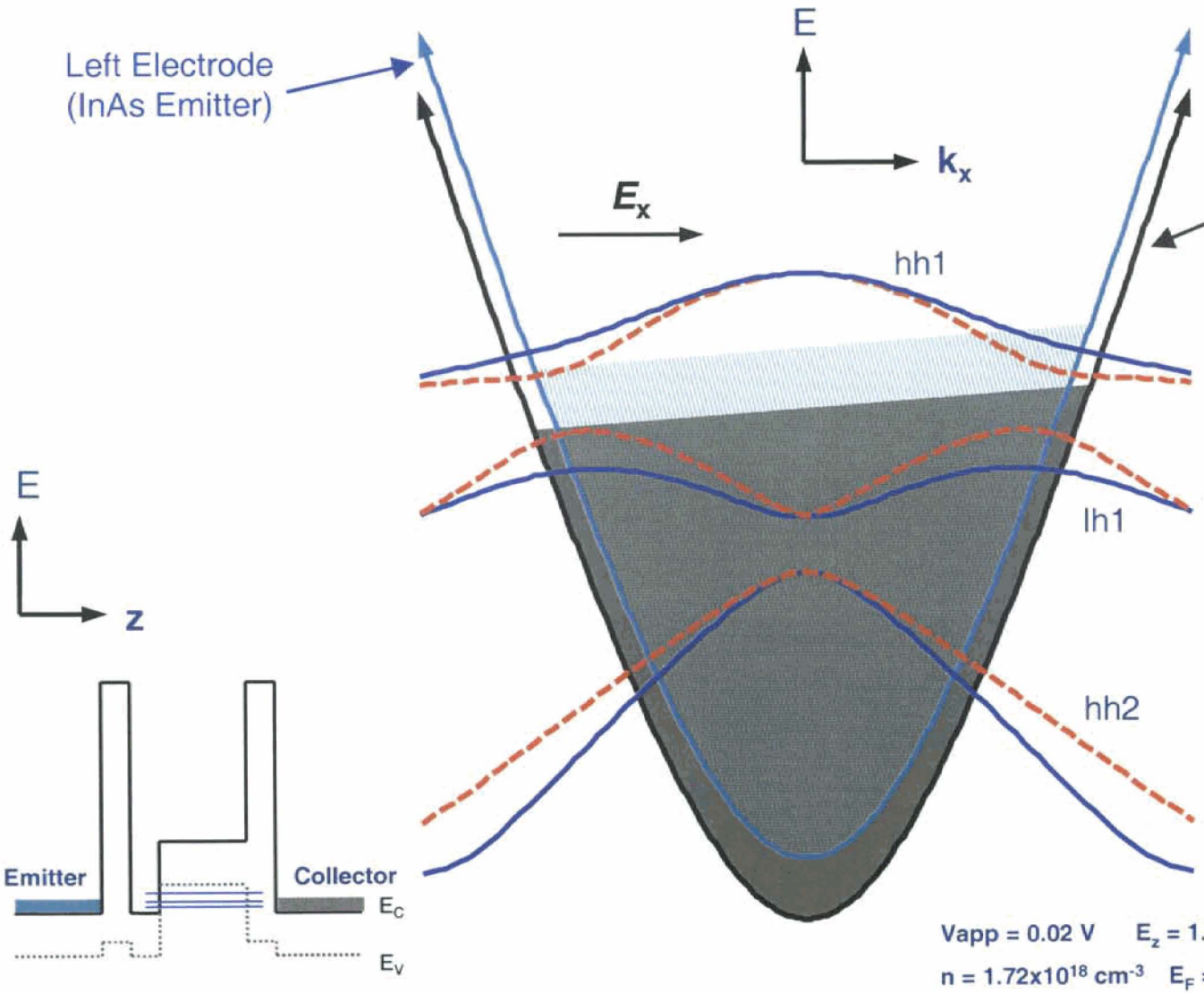
- Can block out light-hole channels by
  - Controlling electrode Fermi levels. Proper biasing.
  - Band structure / strain engineering.

- Salient features of heavy-hole channels:
  - Energy decreases as function of k states, allowing preferential selection of state away from zone center.
  - Small transmission near zone-center.
  - Pronounced difference in size of resonant transmission of two hh1 spin channels away from k=0.

a-RITD Low-Bias Operation



Side-Gated a-RITD Low-Bias Operation
(Additional small Lateral E-Field)



- Large difference in transmission thru two hh1 channels.
- A small lateral E-field creates anisotropy in lateral momemtum distribution.
- Zone center contribution cut-off / de-emphasized.

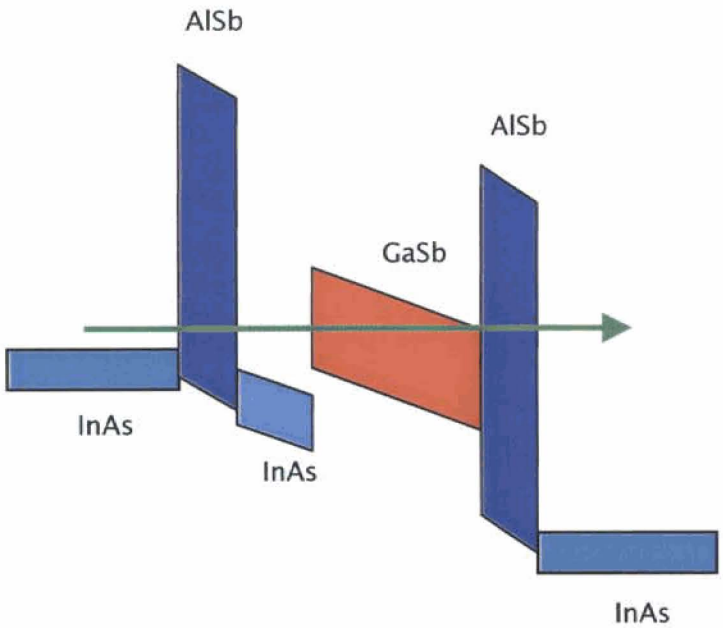
Vapp = 0.02 V $E_z = 1.82 \times 10^4$ V/cm

$n = 1.72 \times 10^{18}$ cm^{-3} $E_F = 0.166$ eV $k_F = 0.036$

$\tau = 1$ ps $E_x = 70$ V/cm $\Delta k_x = 0.001$

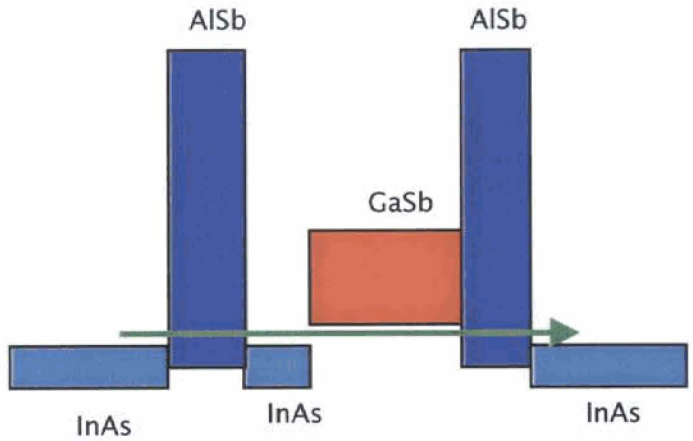
Intraband and Interband Tunneling

Intraband Tunneling



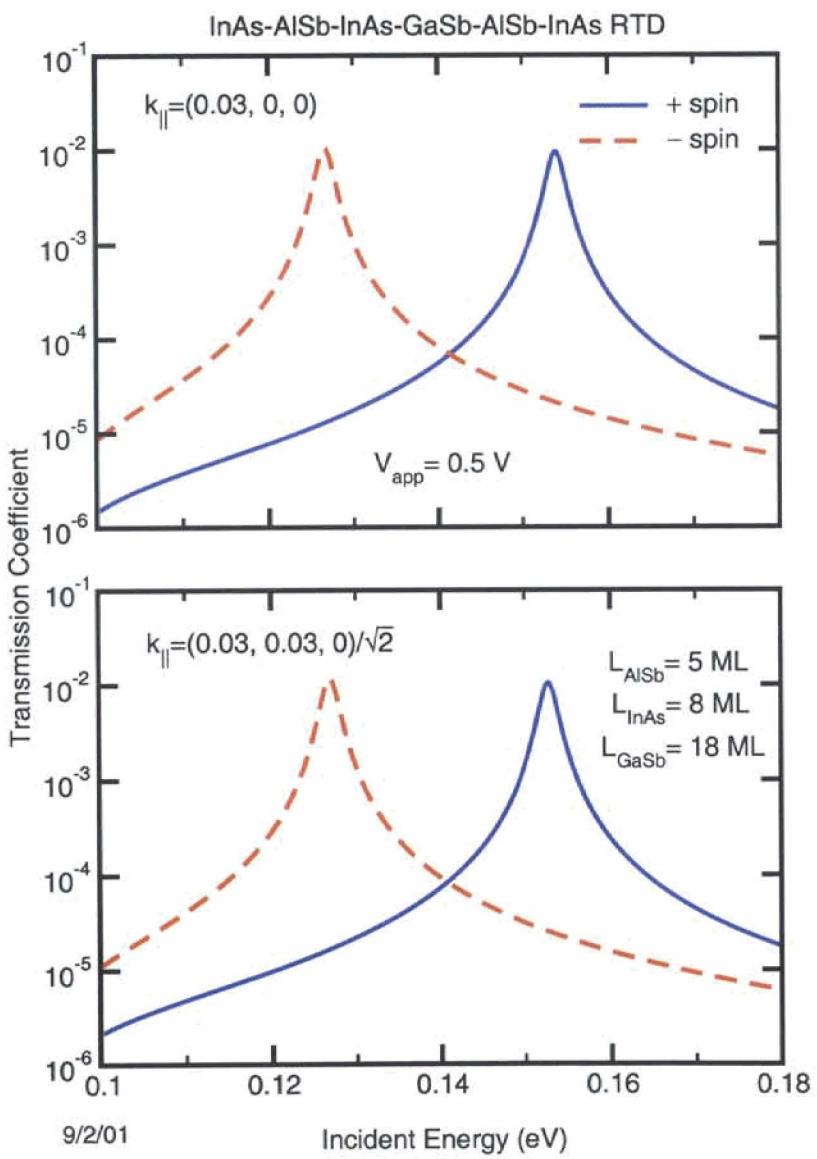
CB → CB → CB

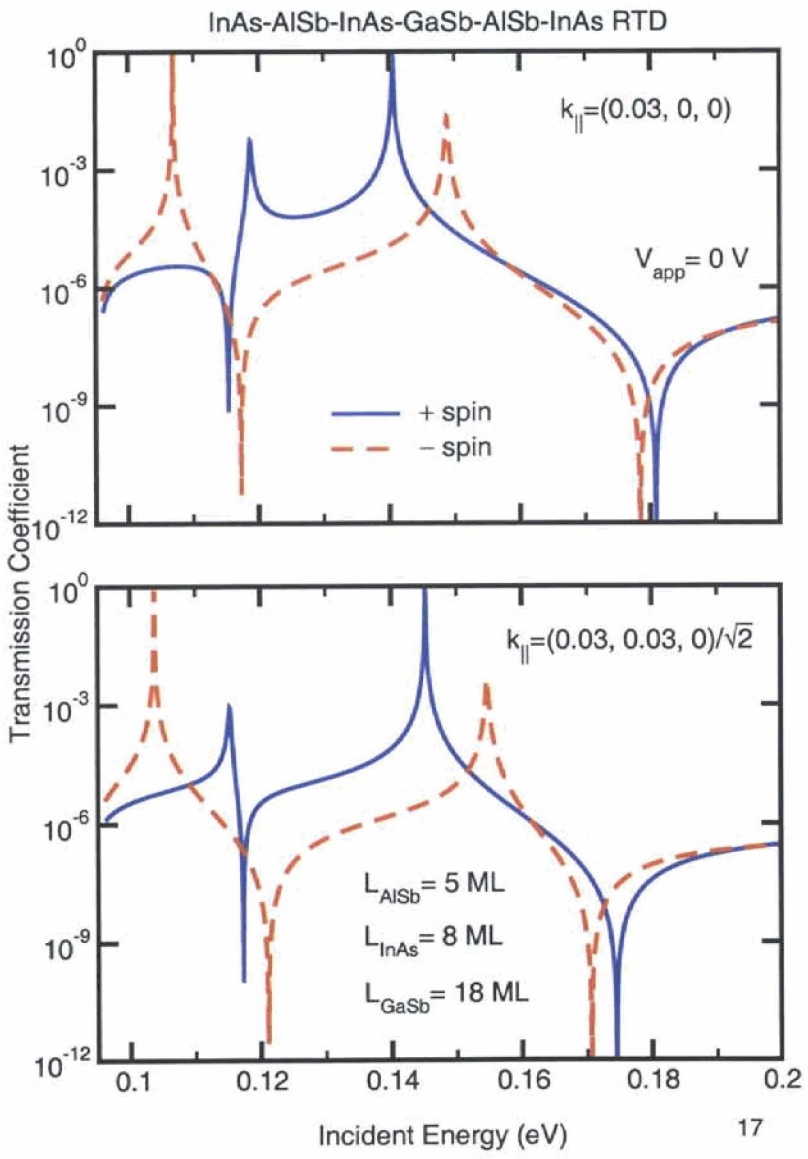
Interband Tunneling



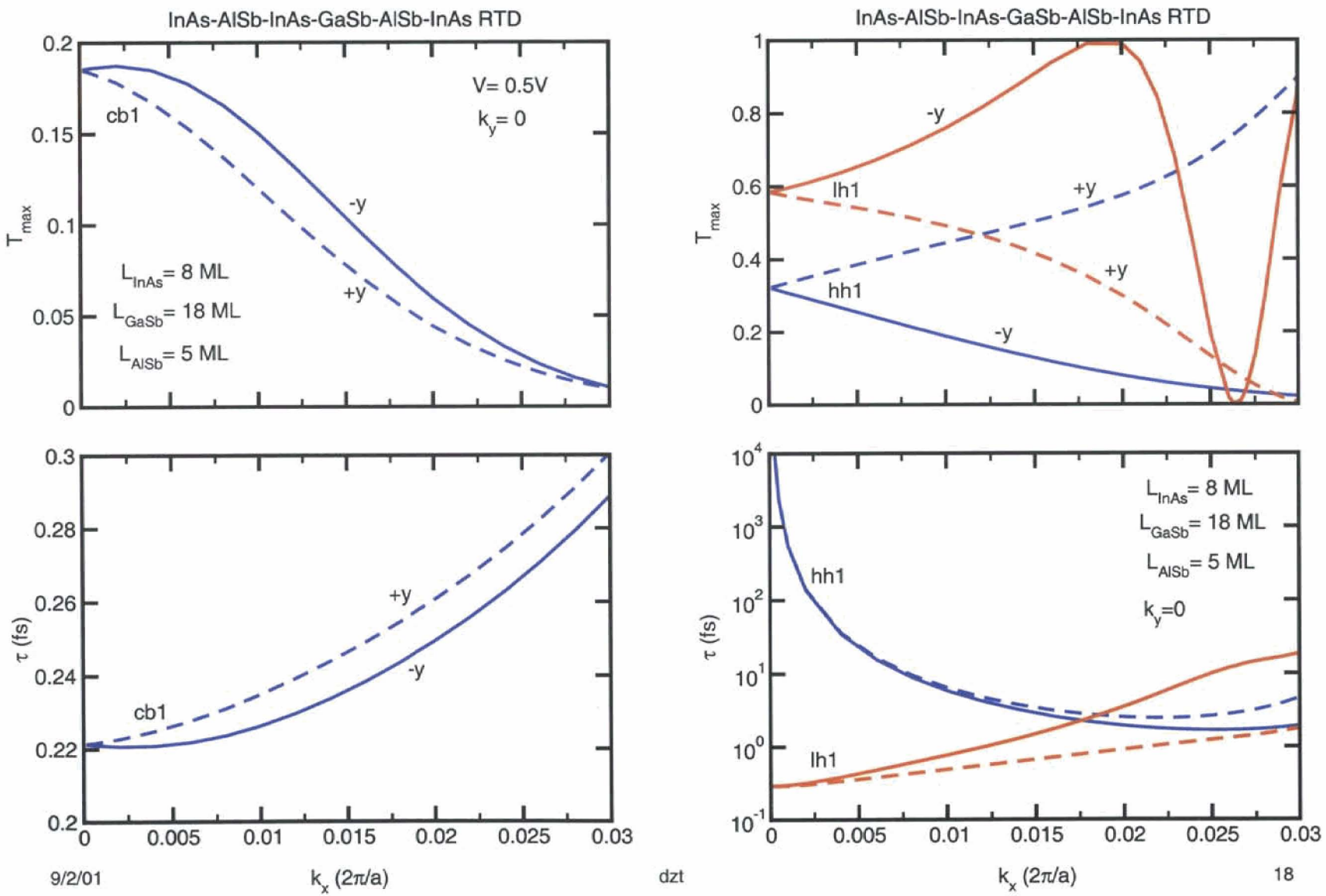
CB → VB → CB

Transmission Coefficients

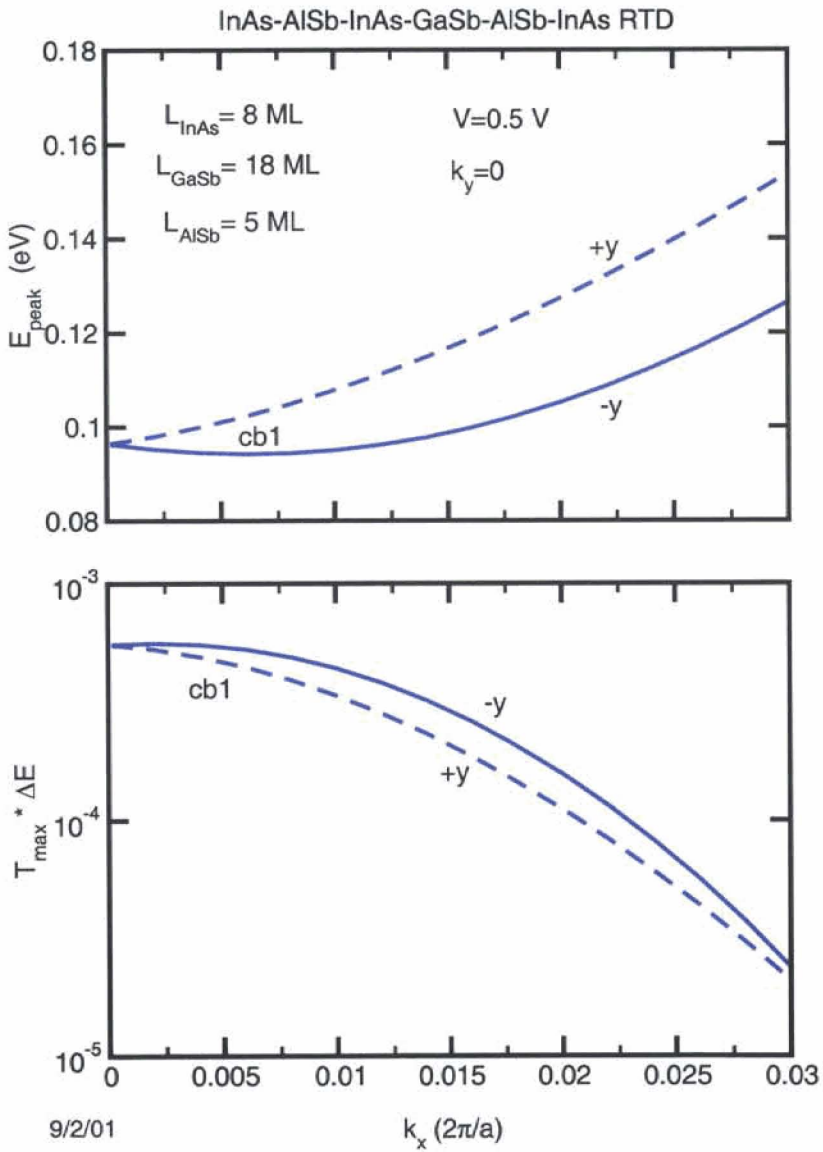


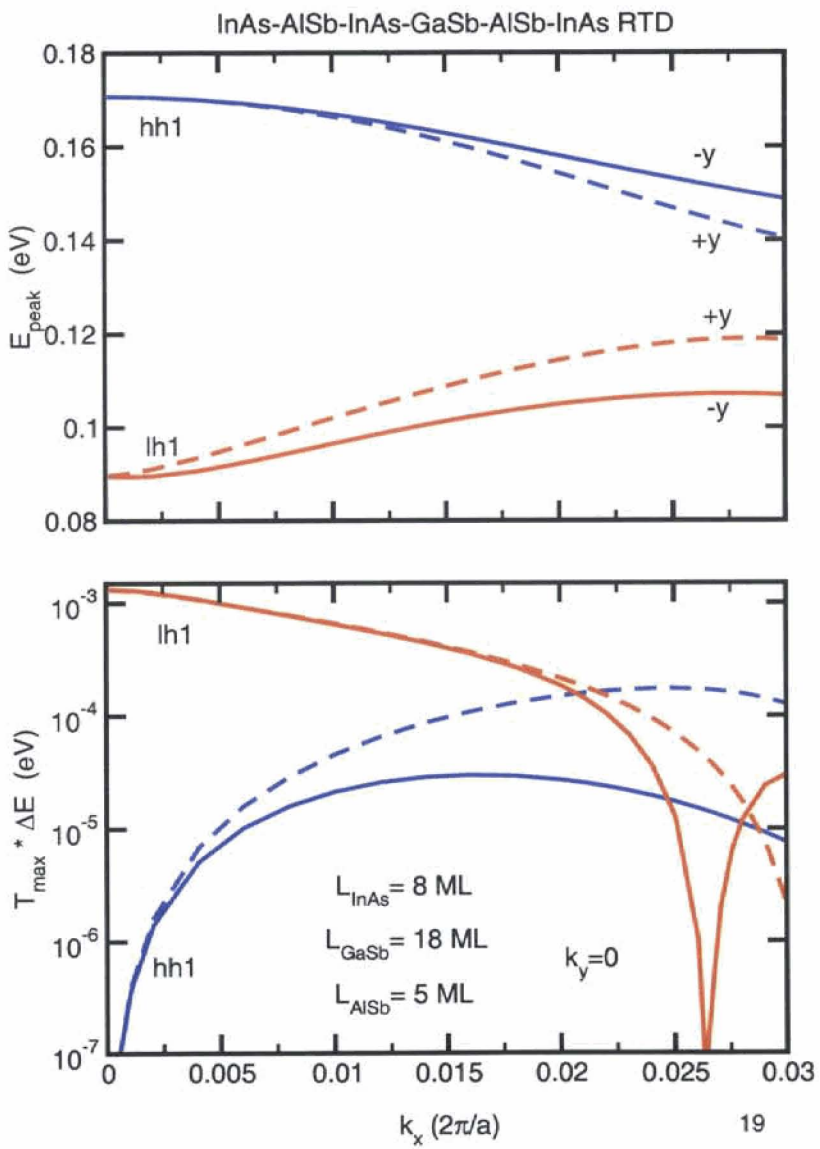


Transmission Peak and Quasibound State Lifetimes



Resonance Position and Peak Strength





Summary

- Exploring the possibility of building a zero-magnetic-field spin polarizer using non-magnetic III-V semiconductor heterostructures.

- Extensive simulations of quantum transport in asymmetric InAs/GaSb/AlSb resonant tunneling structures with Rashba spin splitting.

- New device concept proposed: side-gated asymmetric Resonant Interband Tunneling Diode (a-RITD).