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WORKING PARTY
ON
"ELECTRON TRANSPORT IN SMALL SYSTEMS"
(29 August - 9 September 1988)

IMPORTANT QUESTIONS

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These are preliminary lecture notes, intended only for distribution to participants.

Important Questions

- How long does it take to tunnel through a double barrier?
- Which potential barrier controls tunneling?
- Is low-dimensionality tunneling possible?
- Is resonant tunneling coherent or sequential?

- Tunneling measured from time-resolved luminescence in AlAs-GaAs-AlAs
- $\frac{1}{\tau_e} = \frac{1}{\tau_R} + \frac{1}{\tau_T}$
- For thin barriers and low temperatures $\tau_R >> \tau_T$

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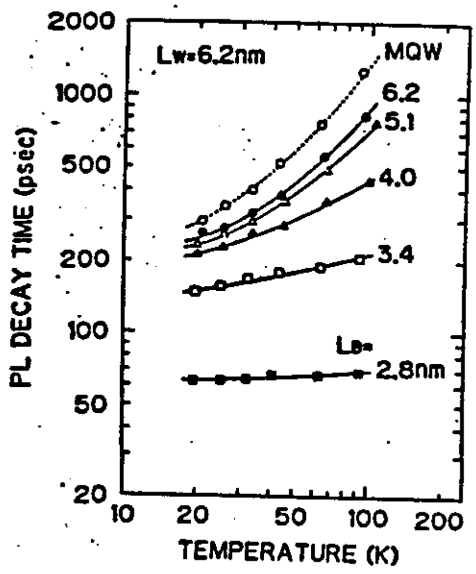
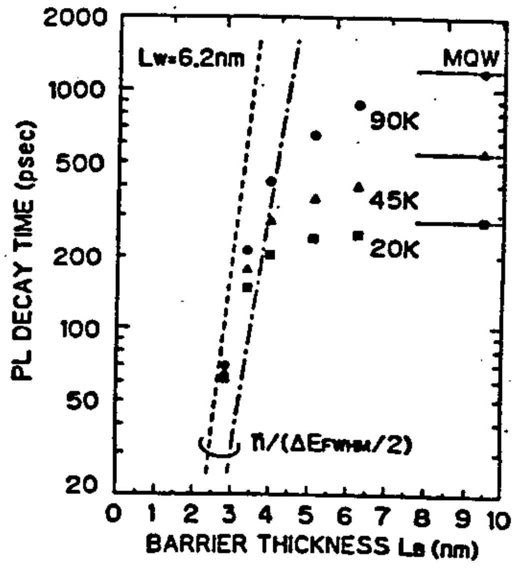


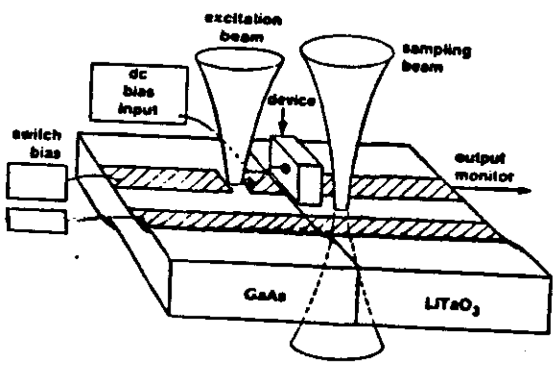


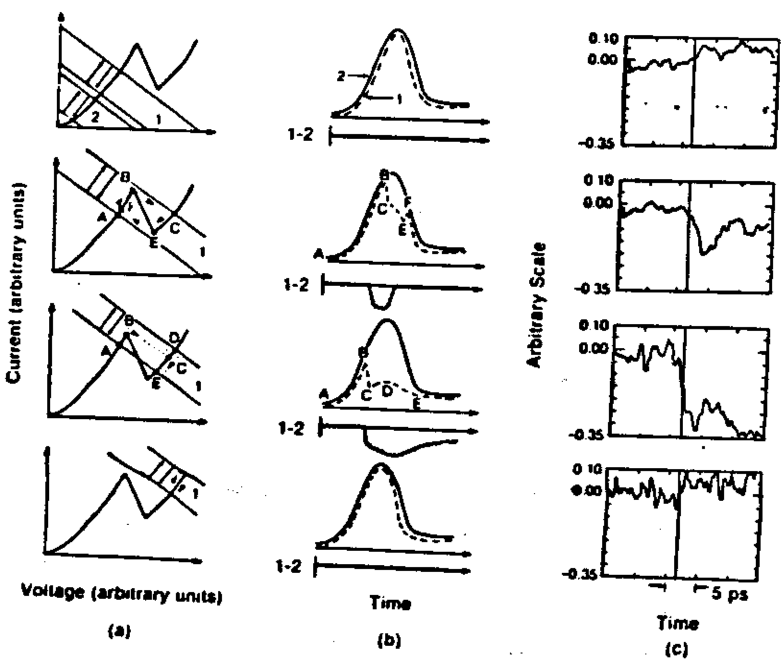
(After Tsuchiya et al., Phys. Rev. Lett. 59, 2356 (1987))

Switching Time in Double-Barrier Diodes

- 2psec. switching time in 45Å-15Å-45Å AlAs-GaAs-AlAs structures
- Intrinsic tunneling time estimated to be ≃1psec.
- Switching speed is comparable to fastest bistable optical devices

(After Whitaker et al., Appl. Phys. Lett. 53, 385 (1988))





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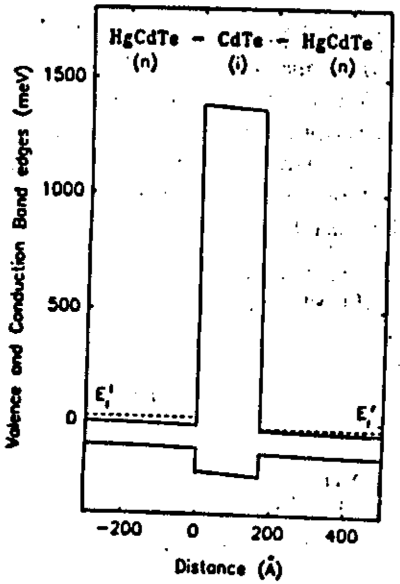
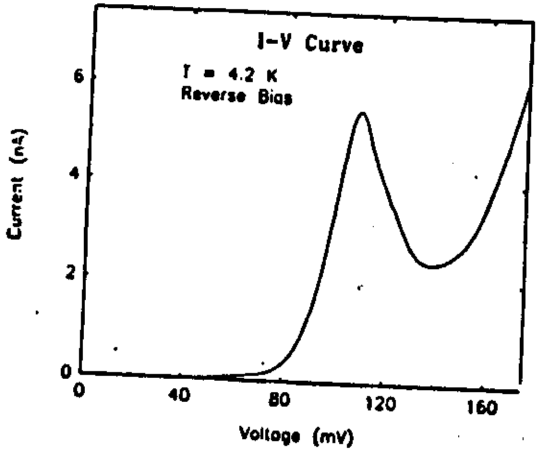
Negative Resistance from Single-Barrier Heterostructures

- When valence-band discontinuity is small, tunneling probability decreases with increasing bias.
- Single-barrier NR observed in HgCdTe-CdTe at low temperatures
- Tunneling time is smaller than in double-barrier structures

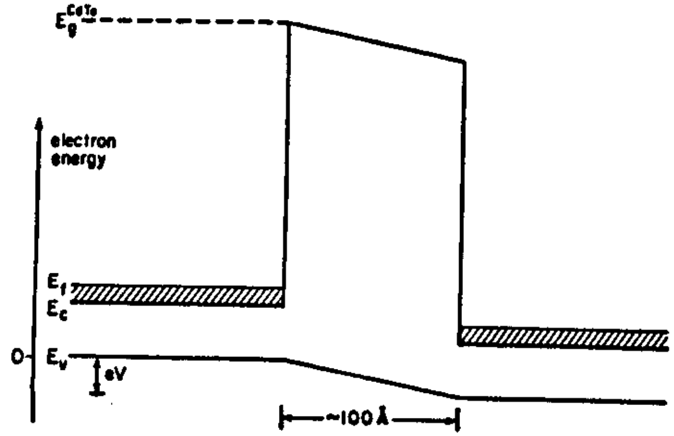


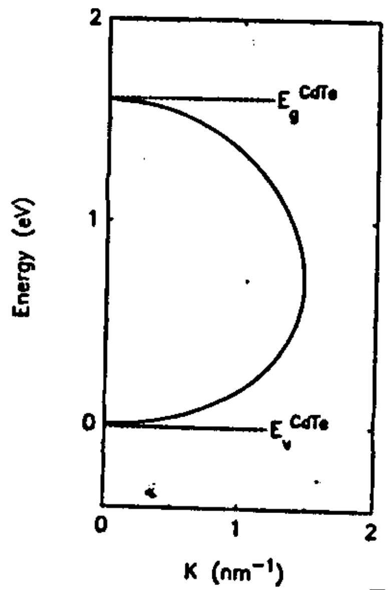


(After Chow et al., Appl. Phys. Lett. 52, 54 (1988).

Negative Resistance from Single-Barrier Heterostructures

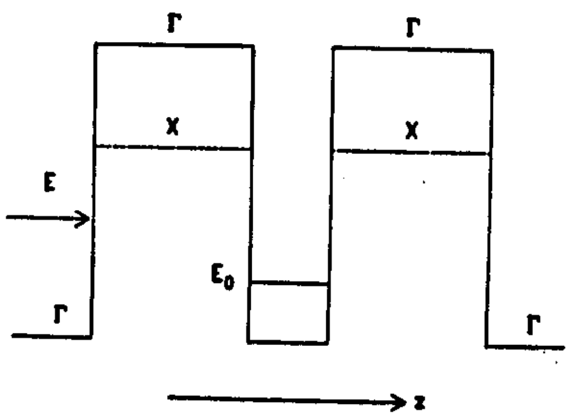
- Negative resistance is a consequence of two effects: increasing density of states available and decreasing tunneling probability.



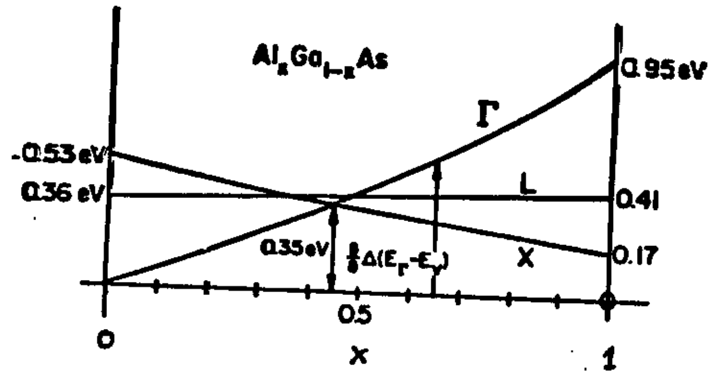


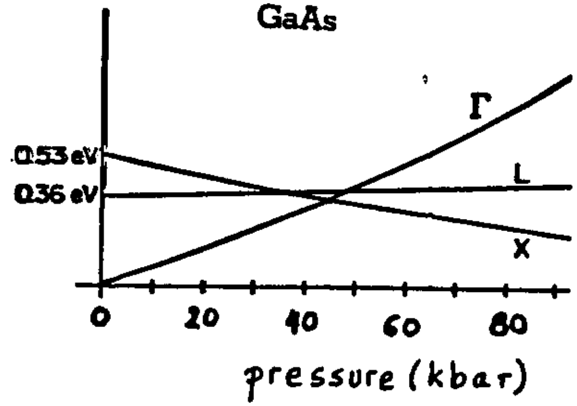
Two-Band Model

$$\frac{\hbar^2 k^2}{2m^*} = E\left(\frac{E}{E_G} - 1\right)$$



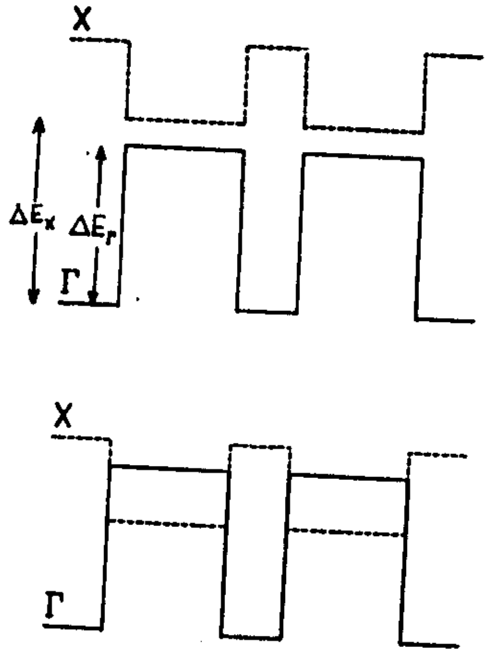
- Which barrier controls:
  - tunneling current?
  - energy levels?





Which potential barrier controls tunneling?

- Hydrostatic pressure applied to direct-gap system makes potential barriers indirect.
- Direct- and indirect-gap barriers have very different pressure coefficients.

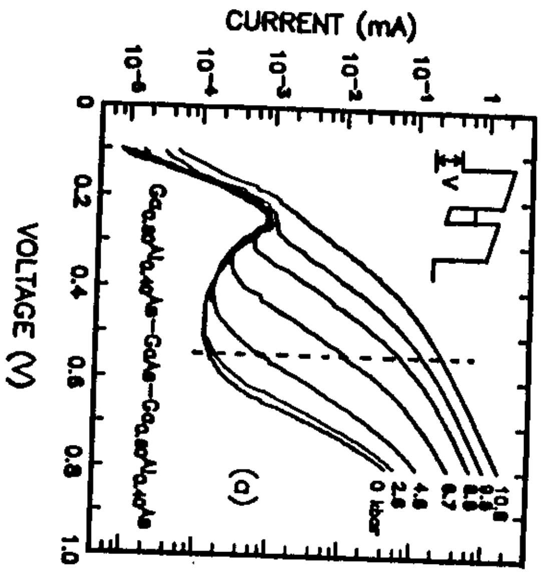


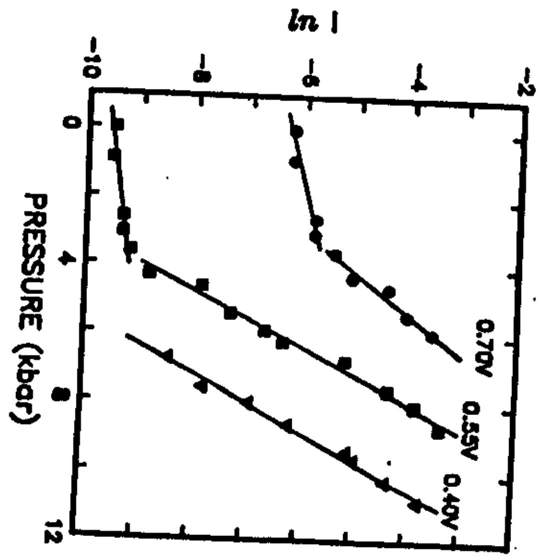
P<4kbar

$$\frac{d}{dp}(\Delta E_\Gamma) \sim -1\ \mathrm{meV/kbar}$$

$$\frac{d}{dp}(\Delta E_X) \sim -10\ \mathrm{meV/kbar}$$

P>4kbar



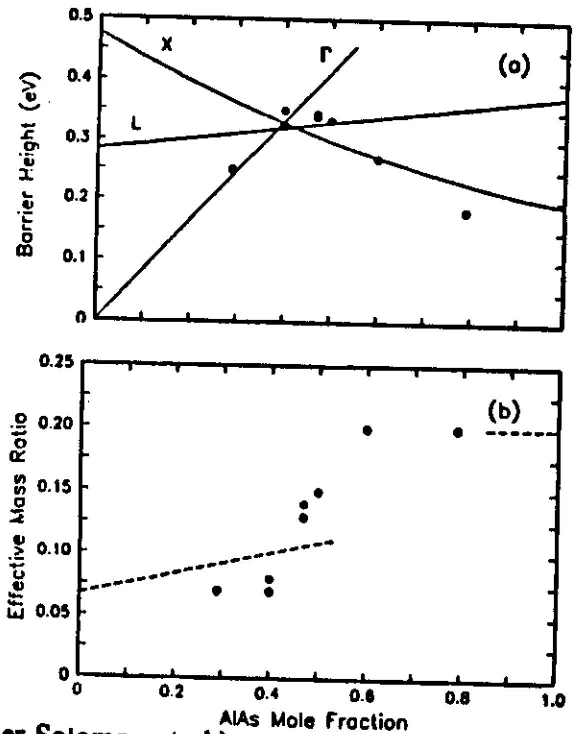


- Tunneling is controlled by the lowest barrier, regardless of symmetry.
- Effective mass for indirect tunneling is light.

Tunneling through Indirect-Gap Barriers

- Tunneling current is controlled by lowest potential barrier, regardless of symmetry.

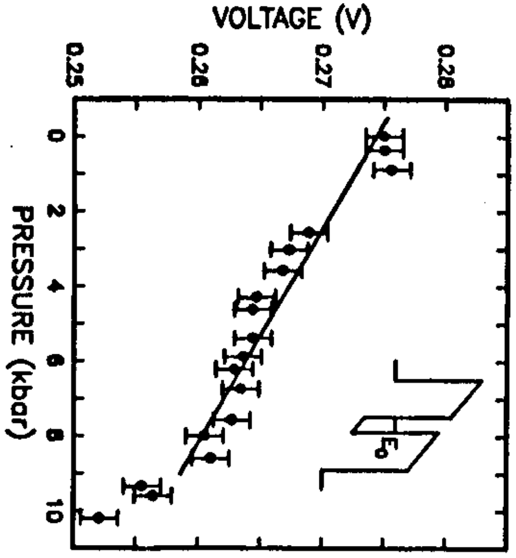
- Similar conclusion reached by
  - Hase et al., J. Appl. Phys. 59, 3792 (1986).
  - P. M. Solomon, S. L. Wright, and C. Lanza, Superlatt. and Microstruct. 2, 521 (1986).



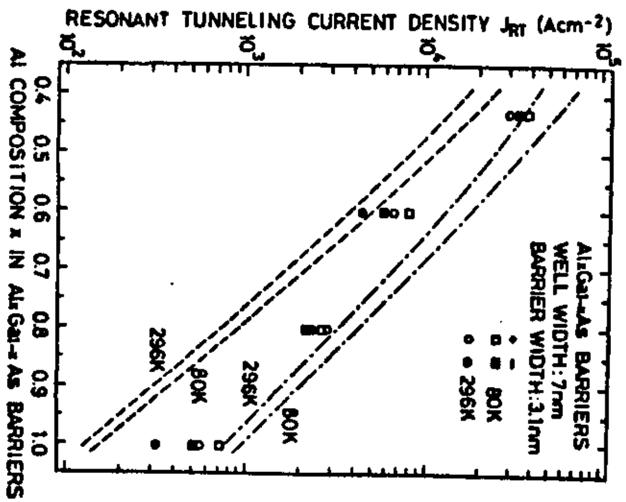
(After Solomon et al.)

Resonant Tunneling Through Indirect-Gap Barriers

- Resonant tunneling is governed by barrier that conserves momentum.

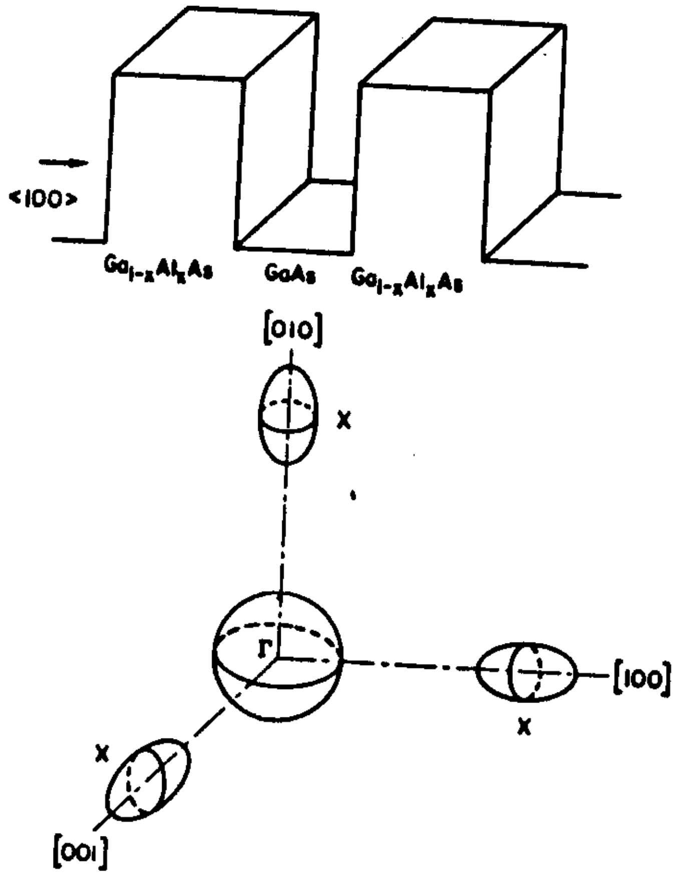


(After Mendez et al., Phys. Rev. B 32, 3454 (1986))



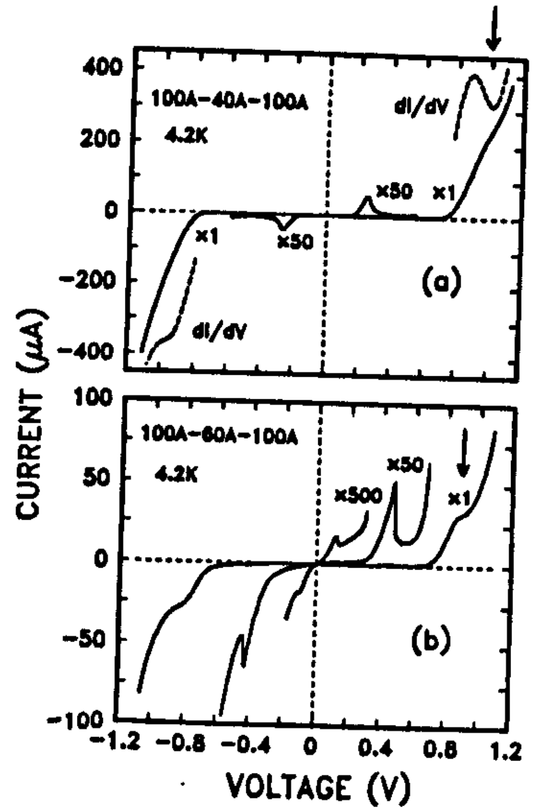
(After Tsuchiya et al., Appl. Phys. Lett. 50, 1503 (1987))

Resonant Tunneling via X-point States

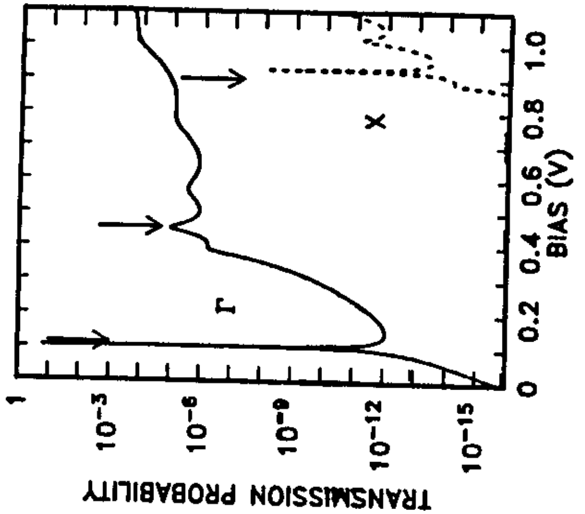


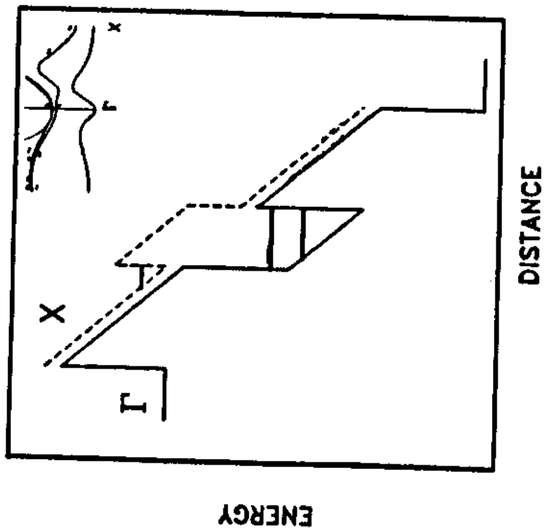
- Momentum parallel to interfaces is conserved for one of the three X-point ellipsoids
- Tunneling mass is heavy

Resonant Tunneling via High-Energy States



- Electrons tunnel resonantly from Γ to X, conserving momentum



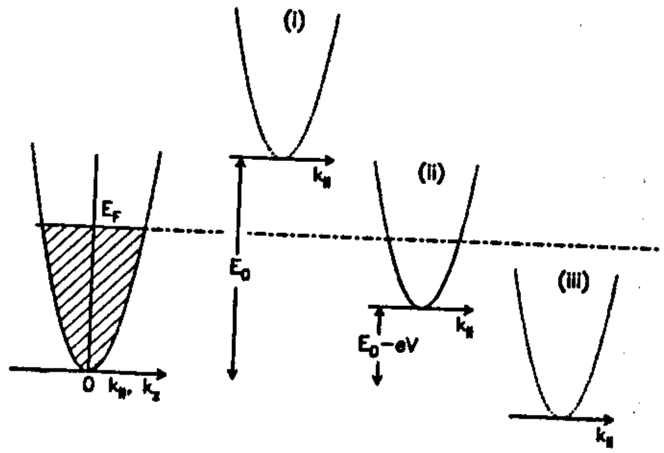


- **Consequences:**

1. **The X-point level can become the ground state**
2. **It is possible to tunnel resonantly through a single AlAs barrier**

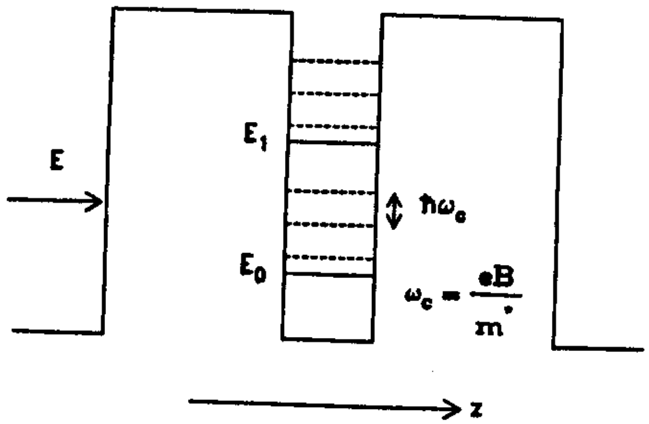
Relative Band Alignment

- **Quantities conserved**
  - **Total energy: $E_T = E_\parallel + E_z$**
  - **Momentum parallel to the layers $k_\parallel$**

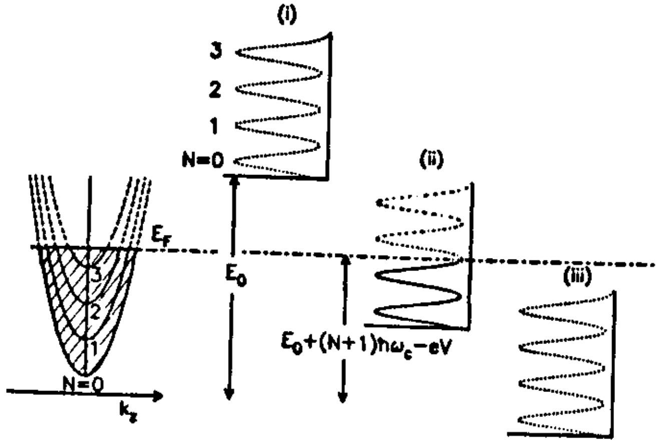


- **I-V characteristic**

Band Alignment in a Magnetic Field

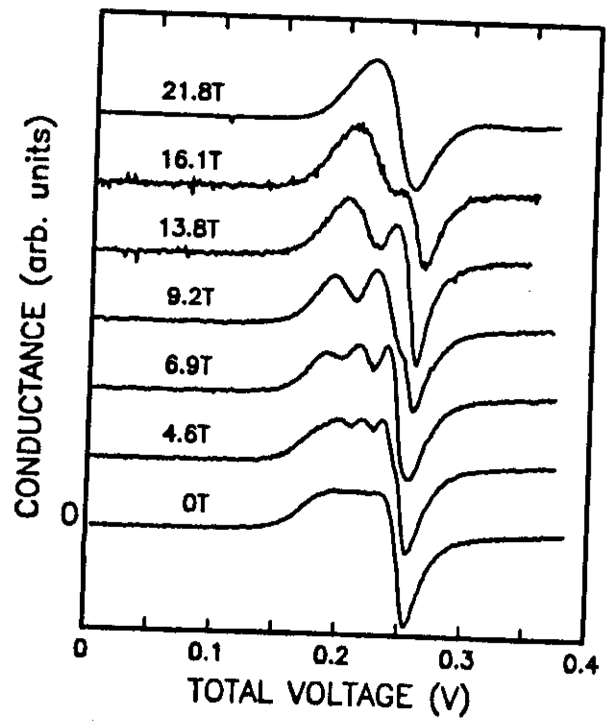


- Magnetic field quantizes motion in both the electrode and the well
- Quantities conserved
  - Total energy
  - Quantum number

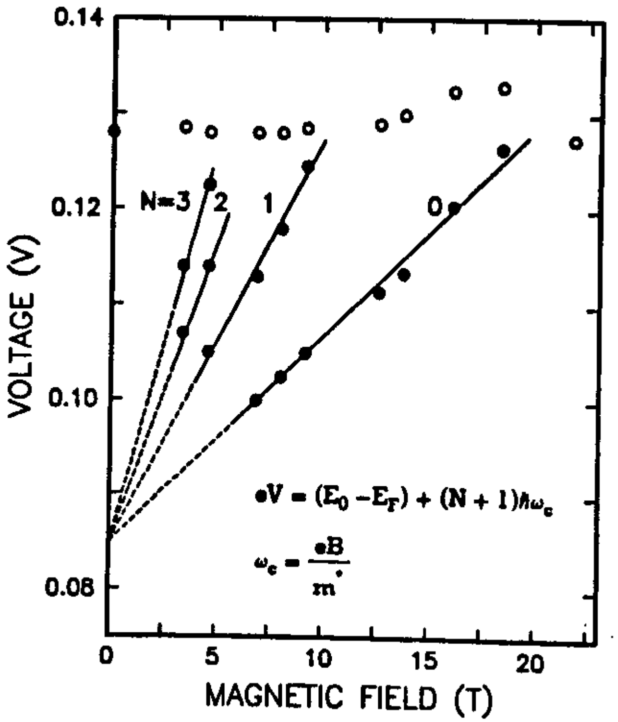


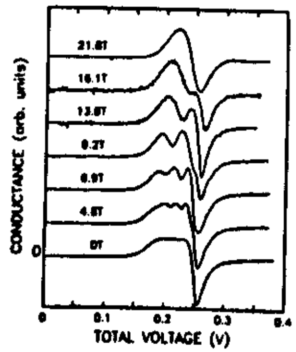
Effect of a Magnetic Field

- Magnetic field parallel to current direction
- Effect is observed in all quantum states (i.e. ground and excited states)
- Effect is independent of temperature (4K-0.5K)



Fan Chart





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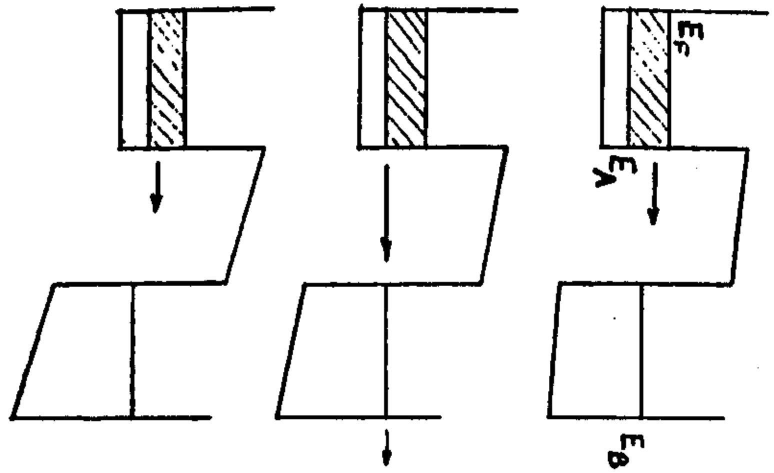
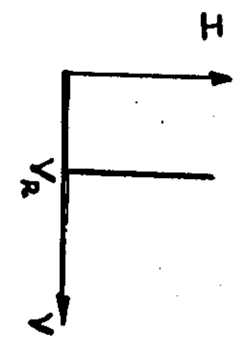
Resonant Tunneling between Two-Dimensional Systems





- $\vec{K}_{tran}$ is conserved
- K_{long} is fixed
- Broadening of E_B leads to finite currents.

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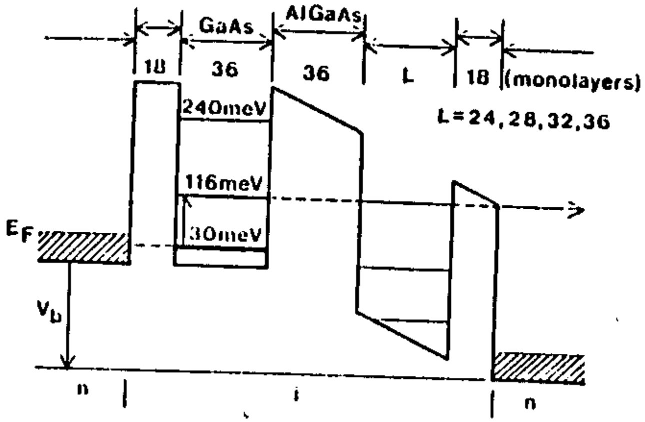
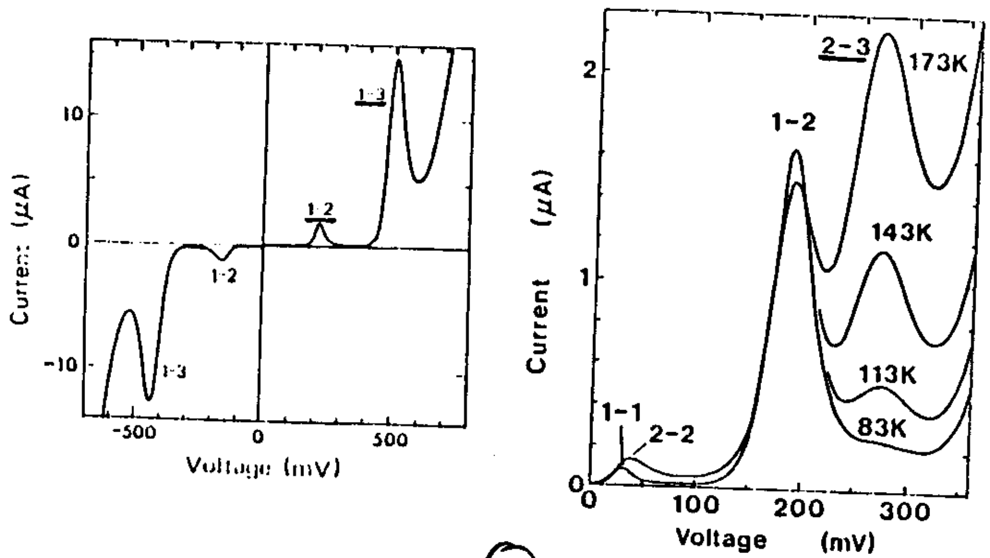
Observation of resonant tunneling in AlGaAs/GaAs triple barrier diodes

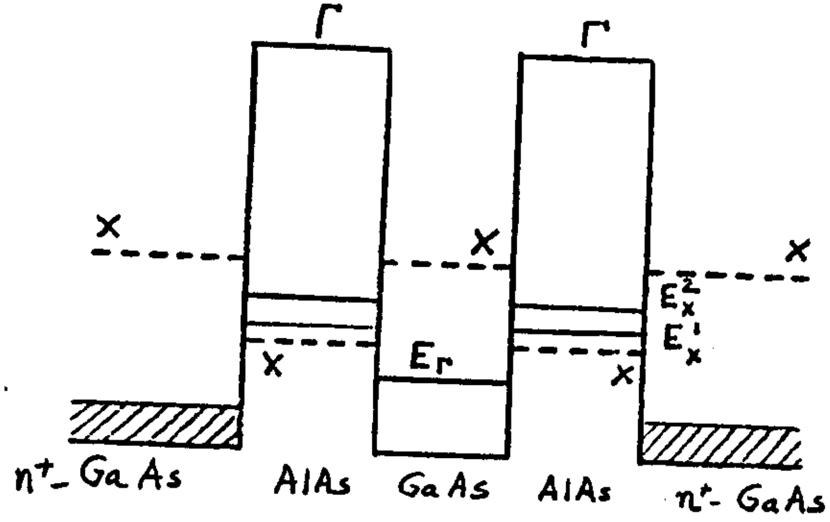
T. Nakagawa, H. Imamoto, T. Kojima, and K. Ohta

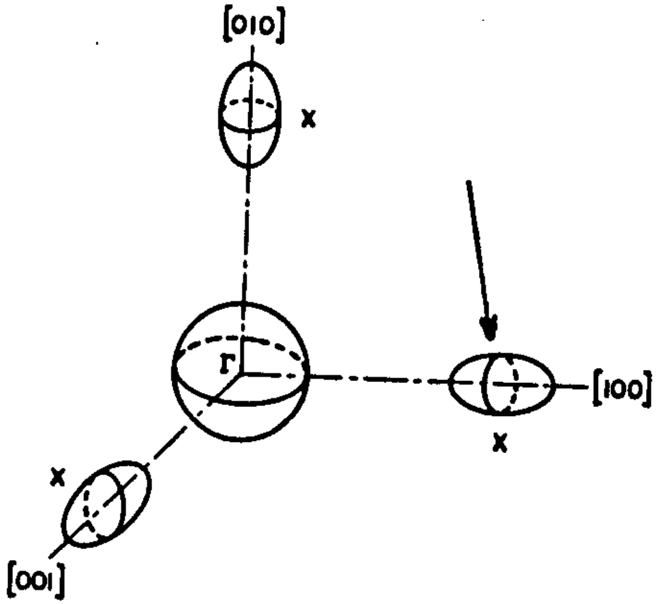




(20)

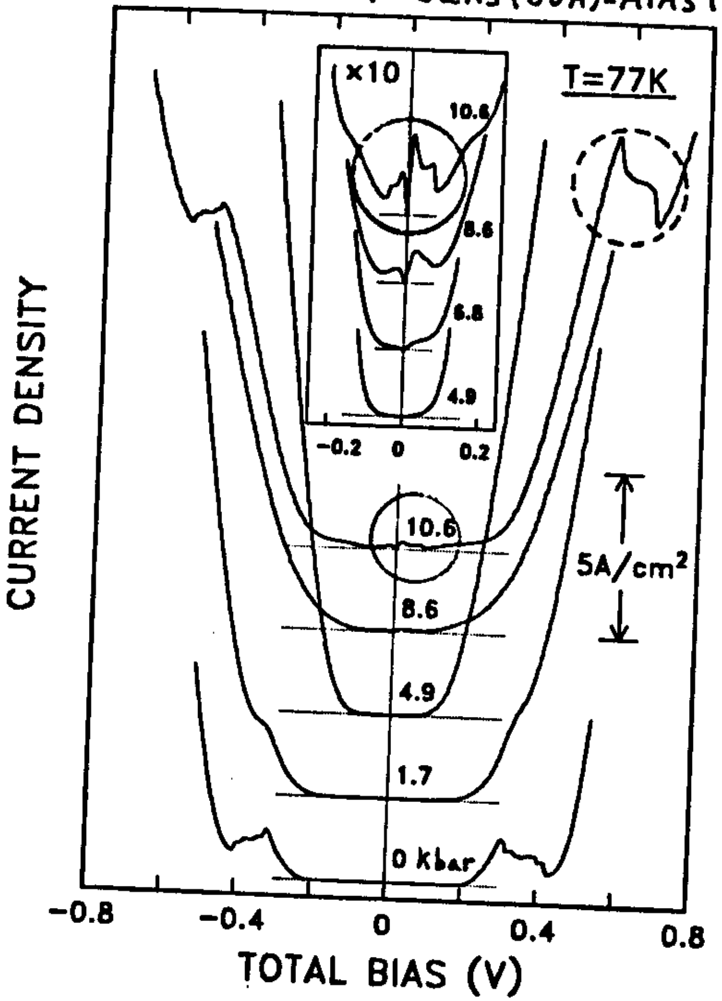
RESONANT X-POINT TUNNELING





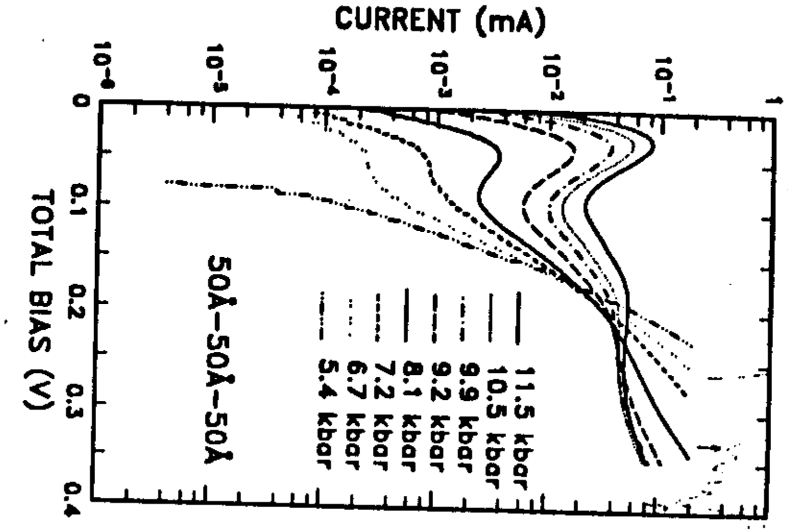
(21)

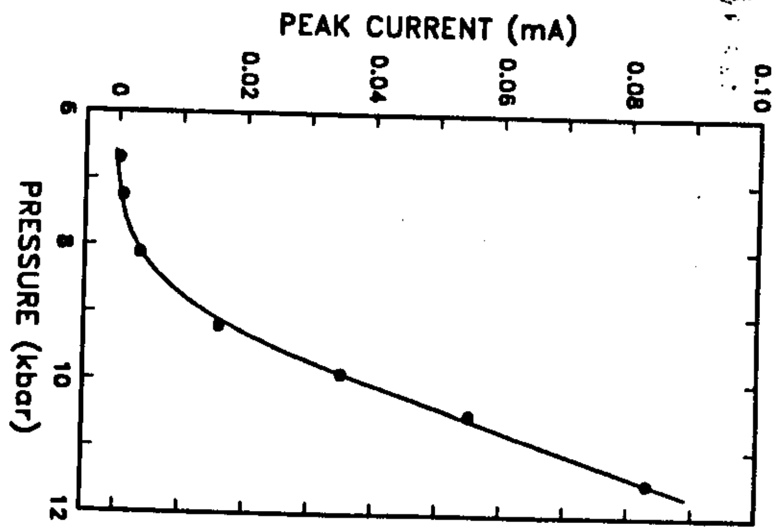
AlAs (50Å) - GaAs (50Å) - AlAs (50Å)



- Main NDR structure recovered
- New NDR feature at very small bias

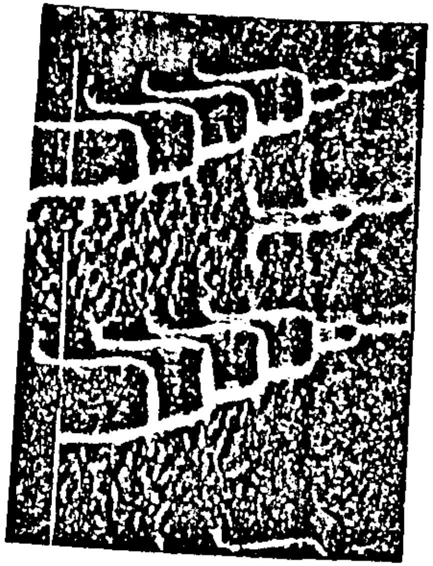
LOW-BIAS I-V CHARACTERISTICS AT HIGH PRESSURES

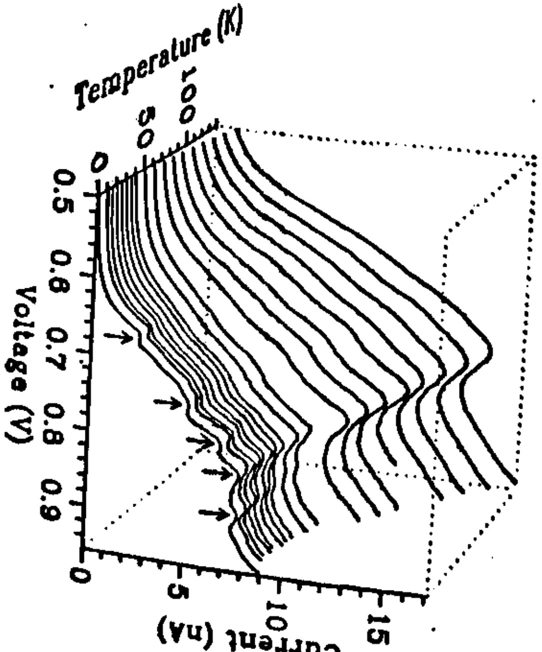




Resonant Tunneling in Zero-Dimension Structures

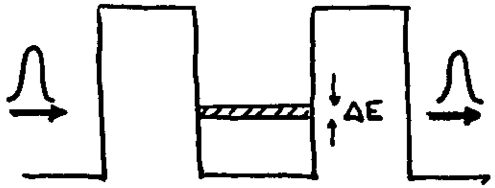
- I-V characteristics shows quantum-size effects (2000Å)



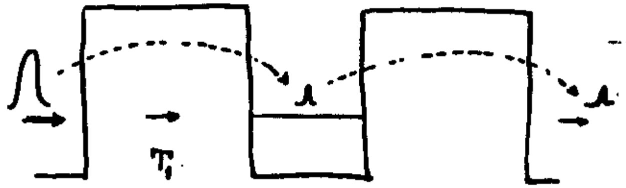


(After Reed et al., Phys. Rev. Lett. 60, 535 (1988))

RESONANT vs SEQUENTIAL TUNNELING



COHERENT



INCOHERENT

- "Resonant" if $\tau_{transit} \ll \tau_{inelastic}$
- "Sequential" if $\tau_{transit} \gg \tau_{inelastic}$

- Negative Resistance is common to both
- Current Density:

  Theory : { * no difference (Weil and Vinter) ; * large difference (Buttiker) }

  Experiment : maybe differences

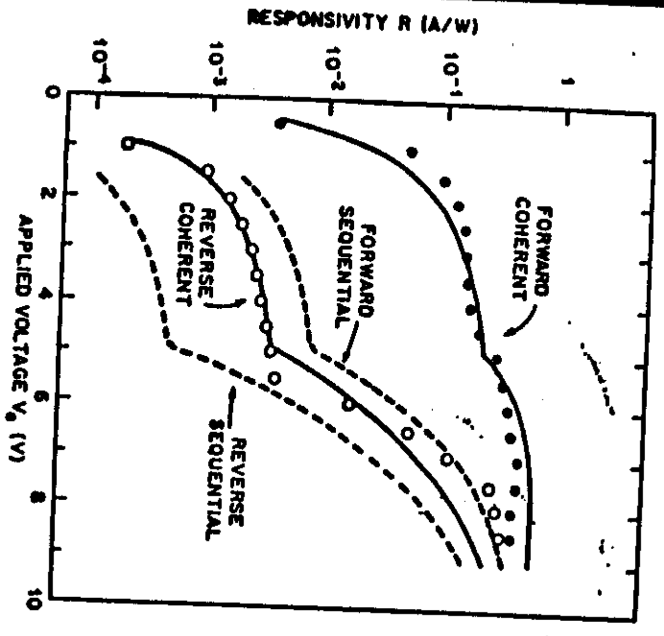
Resonant Tunneling or Sequential Tunneling?

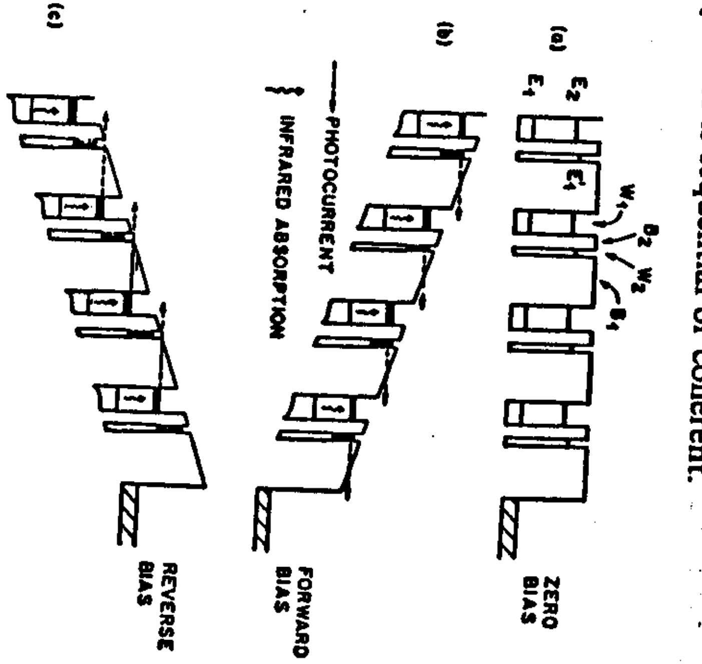
- Ideal values of 100Å-40Å-100Å heterostructure
  - Maximum Current: $\simeq$30 A/cm^2
  - Maximum Charge: $\simeq$7x10^{11}cm^2
  - Lifetime:$\simeq$4x10^{-9}sec
- Experimental values:
  - Maximum Current: $\simeq$10^{-3} A/cm^2
  - Maximum Charge: << Ideal value
- Scattering Time in GaAs:$\simeq$10^{-11}sec.

- For thick barriers, sequential tunneling dominates

Coherent Tunneling in a Double-Barrier Superlattice

- Photoexcited electrons tunnel resonantly when E_2 and E'_1 are aligned
- Photocurrent is different whether the process is sequential or coherent.

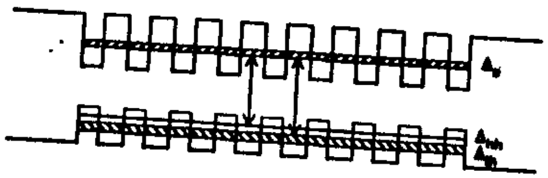




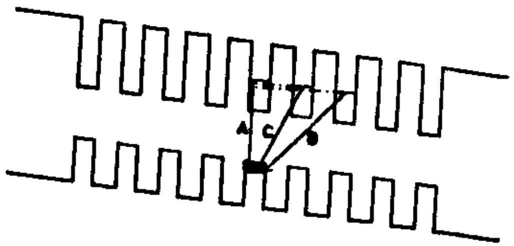
(After Choi et al., Phys. Rev. Lett. **59**, 2459 (1987))

Stark Localization in Superlattices

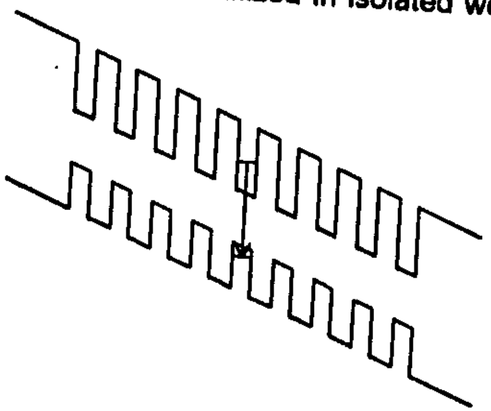
- At zero field, electrons are itinerant. (Minibands result from coupling among states of individual wells.)



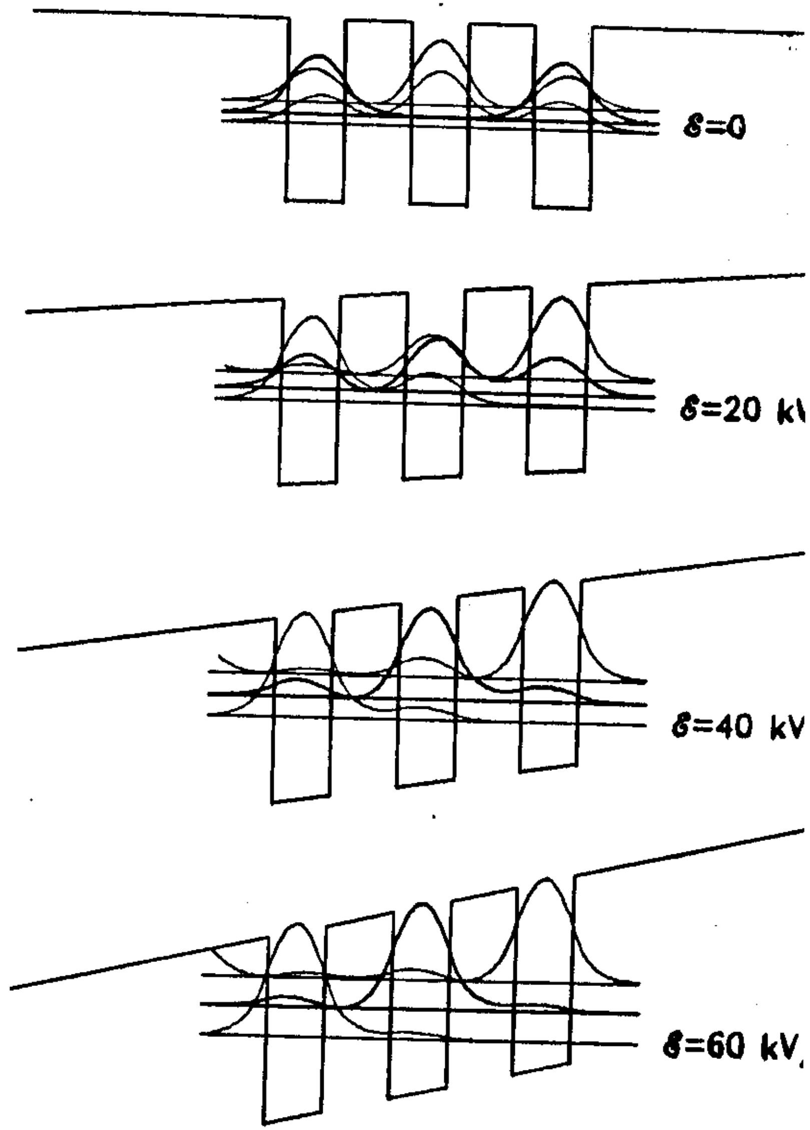
- With field, coupling is limited to adjacent wells.

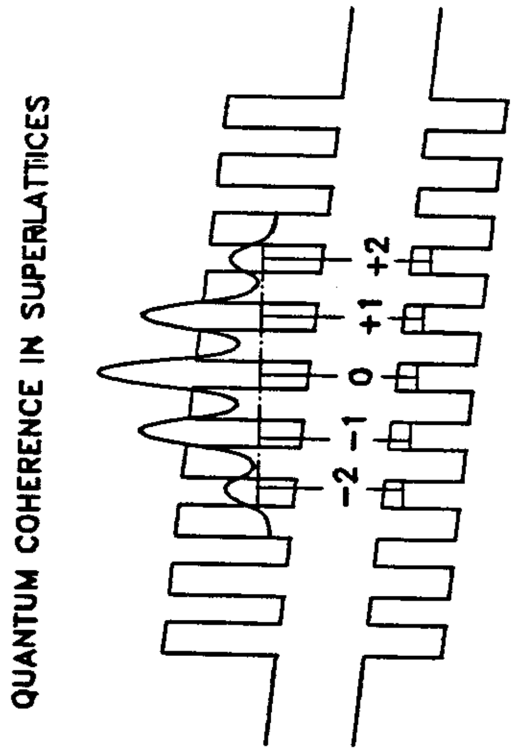


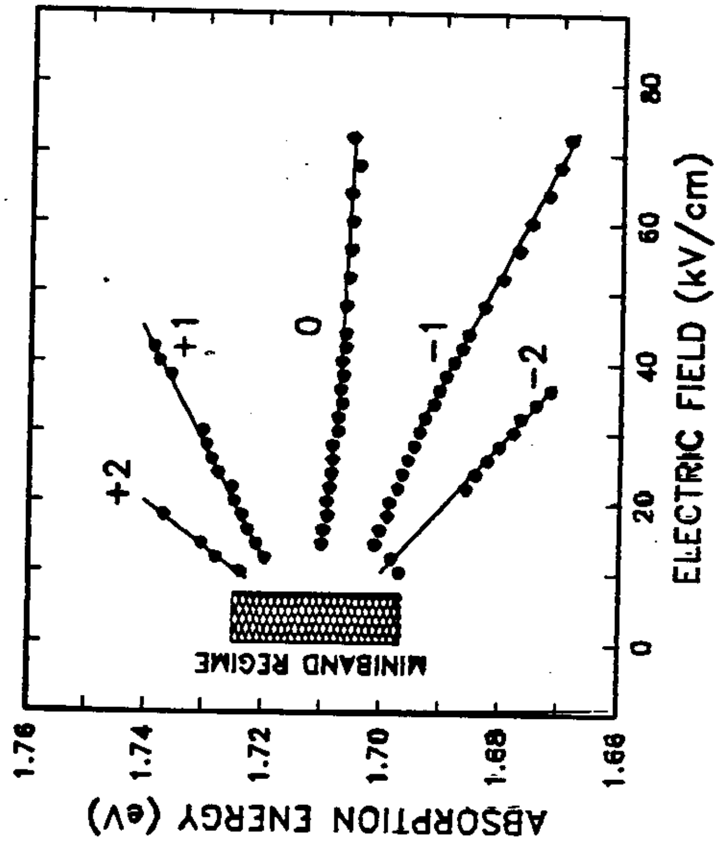
- At high fields ($e\mathcal{E}D>\Delta$), coupling disappears and electrons become localized in isolated wells.



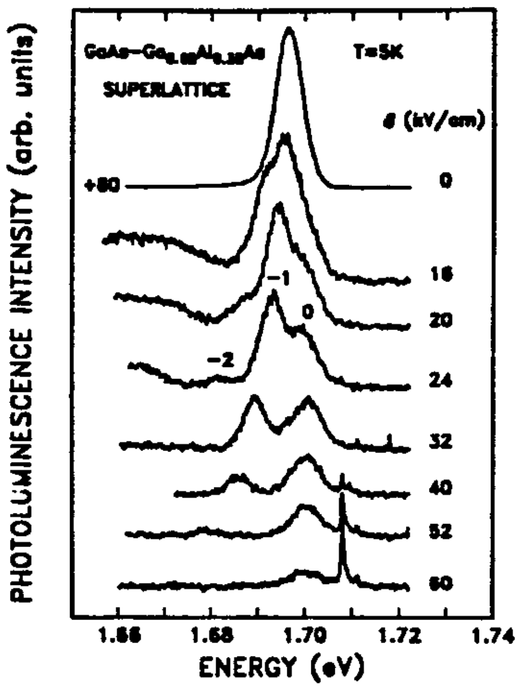
- <u>Optical transitions experience "blue" shift</u> $\simeq\Delta_e+\Delta_h/2$.

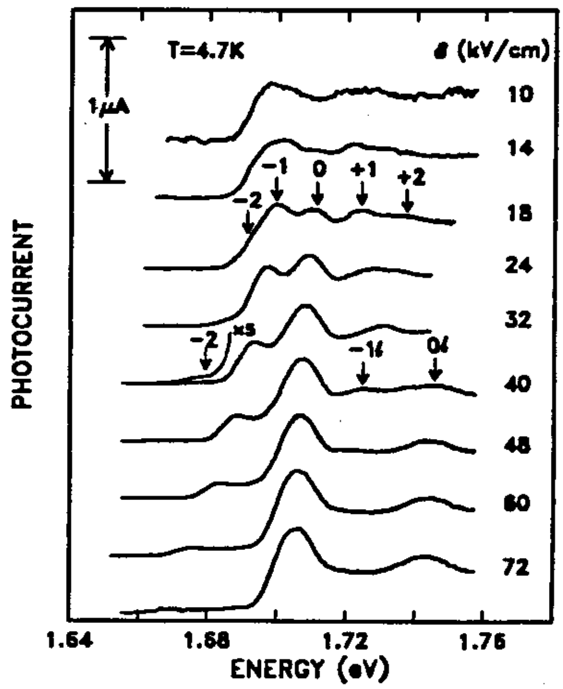






Stark Localization in Superlattices under an Electric Field





- "Blue" shift of band-edge interband transition
- Additional Stark-ladder transitions
- Enhancement of exciton binding energy