Lecture 6 - Quantum effects in heterostructures, II - Outline

- **Continue wells, wires, and boxes from L 5**
- **Coupled wells and superlattices**

  Two coupled quantum wells:

  1. Energy level system
  2. Impact of separation/coupling

  Superlattices:

  1. Energy levels
  2. Applications

  Specialized multiple well structures and their applications

  1. Cascade lasers
  2. QWIP detectors
  3. RTDs

  (just a mention now, more later on)

- **Resonant tunneling diodes (RTDs)** (as time permits)

  Basic structure and theory: Current-voltage characteristic

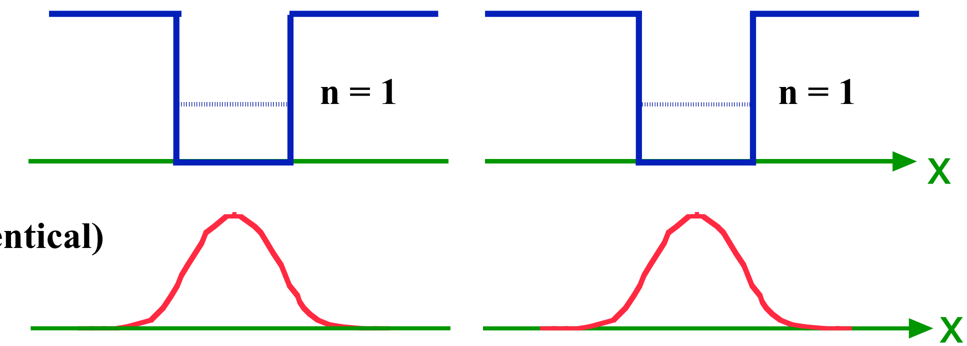
  Specific examples:

  1. GaAlAs/GaAs
  2. InGaAs/InAs/AlAs/InP
  3. Type II tunneling

  Applications

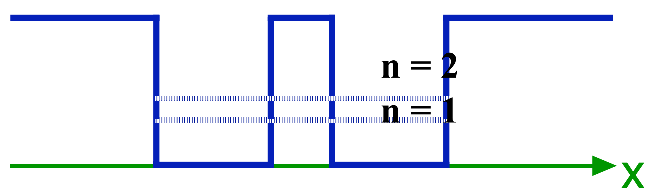
Quantum heterostructures - coupled quantum wells

Two isolated quantum wells: identical, isolated levels

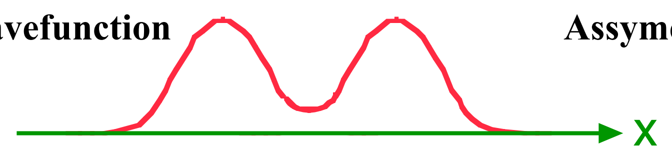


Wavefunctions (identical)

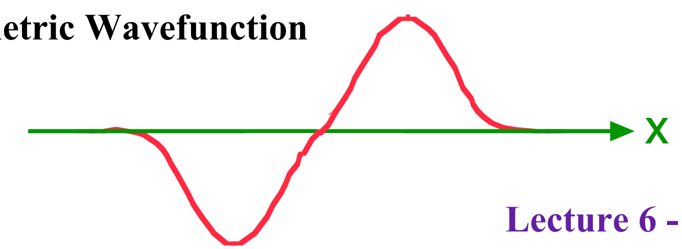
Two coupled quantum wells: isolated levels split into two levels for the combined system, slightly shifted from the original position



Symetric Wavefunction

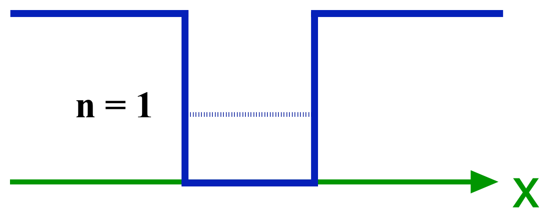


Assymetric Wavefunction

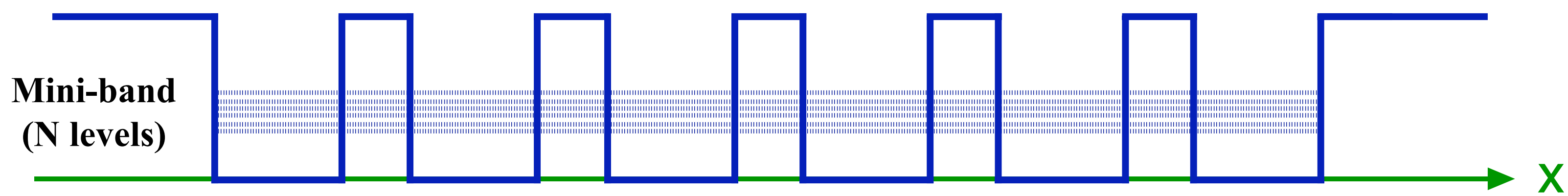


Quantum heterostructures - superlattices

Isolated quantum well:



N coupled quantum wells: isolated levels split into N levels for the combined system, all slightly shifted from the original position and forming a mini-band of states



Superlattices and mini-bands

(Image deleted)

See Y.H. Wang, S.S. Li and Pin Ho, "Voltage-tunable dual-mode operation InAlAs/InGaAs quantum well infrared photodetector for narrow- and broadband detction at 10 um," Appl. Phys. Lett. 62 (1993) 621.

Quantum heterostructures - applications

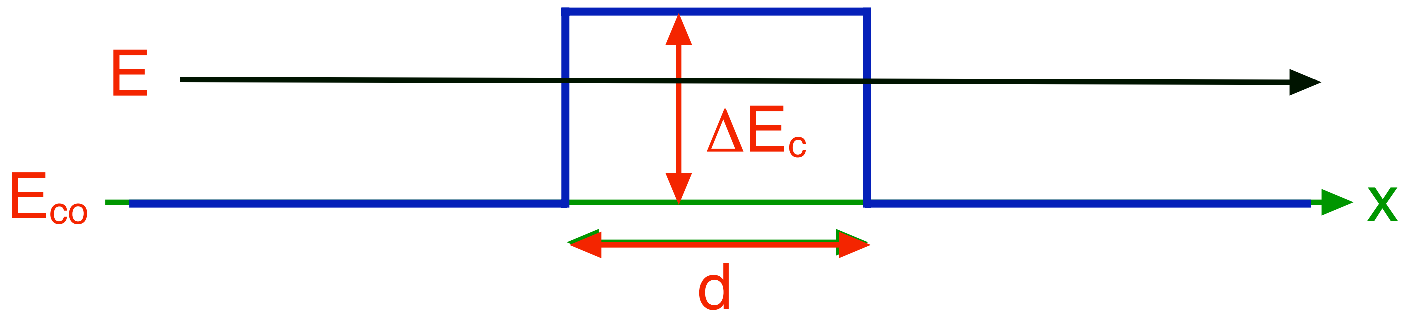
Applications:

Laser diode active layers	(Lectures 19, 20)
QWIP structure	(Lecture 22)
Cascade laser structure	(Lecture 20)
Resonant tunneling diodes	(today)

Quantum Tunneling through Single Barriers

Transmission probabilities - Ref: Jaspirit Singh, Semiconductor Devices - an introduction, Chap. 1

Rectangular barrier

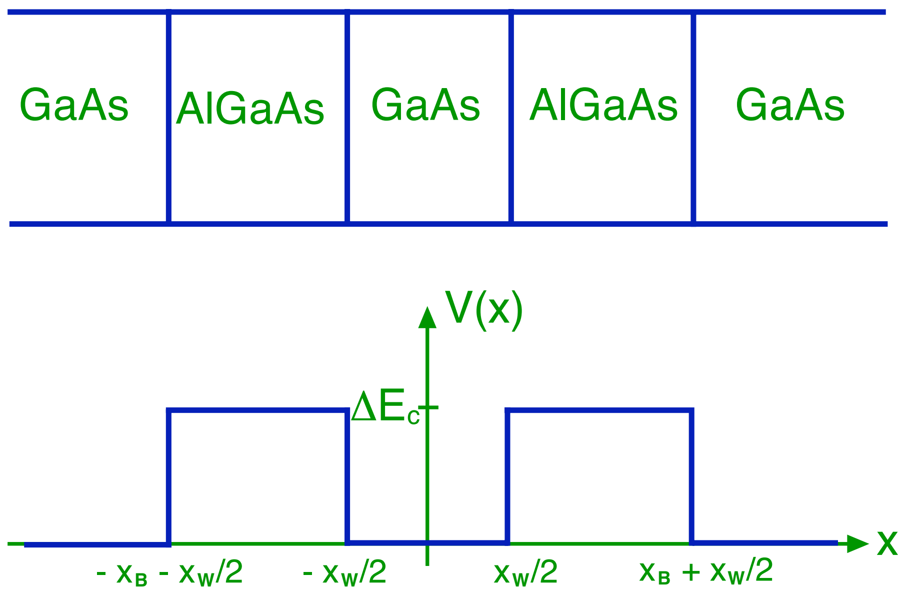


$$T = 4 \Big/ \left\{ 4\cosh^2 \alpha d + \left[(\alpha / k) - (k / \alpha \right] 2\sinh^2 \alpha d \right\}$$

$$where \quad k^2 = 2m^*(E - E_c) \big/ \hbar^2 \;\; and \;\; \alpha^2 = 2m_o\left[\Delta E_c - (E - E_c) \right] \big/ \hbar^2$$

Common 1-d potential energy landscapes, cont.

A one-dimensional resonant tunneling barrier:



Classically, electrons with $0 < E < \Delta E_c$ can again not pass from one side to the other, while those with $E > \Delta E_c$ do not see the barriers at all.

Quantum mechanically, electrons with $0 < E < \Delta E_c$ with energies that equal energy levels of the quantum well can pass through the structure unattenuated; while a fraction of those with $E > \Delta E_c$ will be reflected by the steps.

Resonant tunneling diodes

Conduction band edge profiles:

Unbiased:

Biased:

A. At resonance
100% transmission

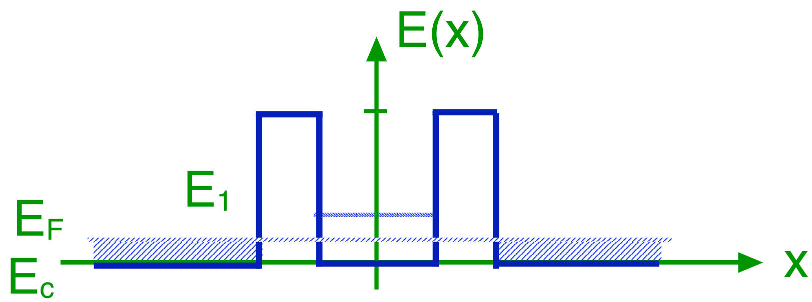
B. Above resonance
no transmission

I-V characteristics:

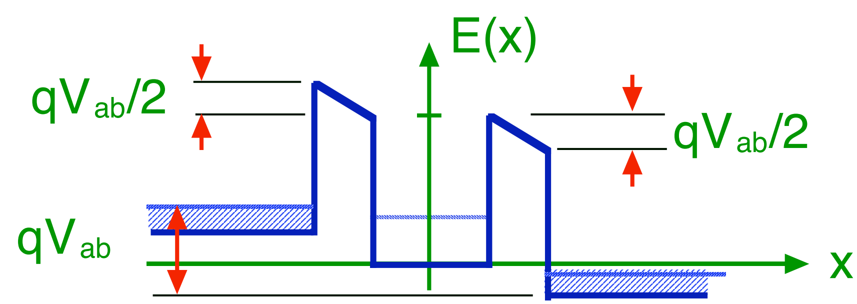
Resonant Tunneling Diode - theoretical i-v

Model for discussion

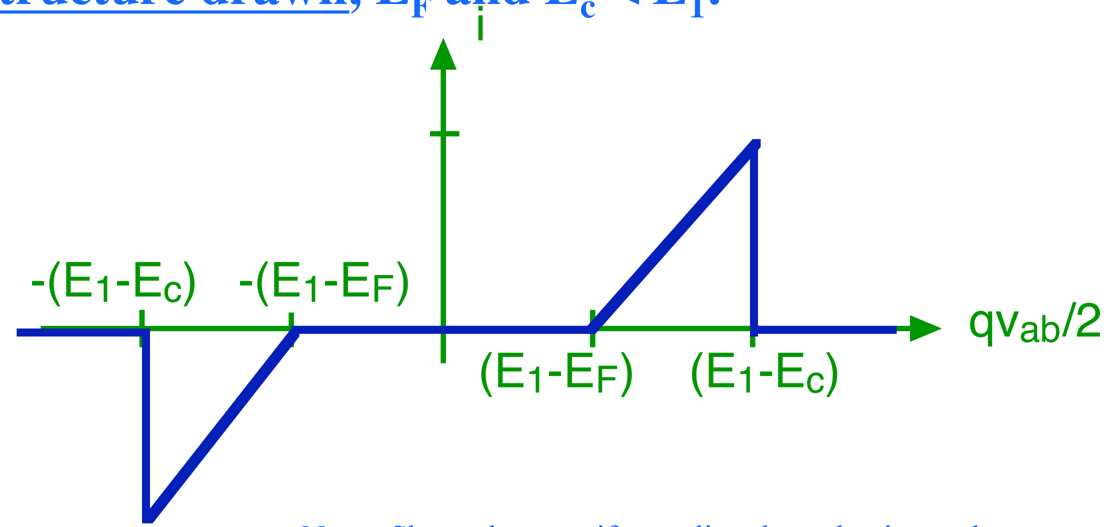
Unbiased:



Under bias:



Ideal i-v for structure drawn, E_F and $E_c < E_1$:

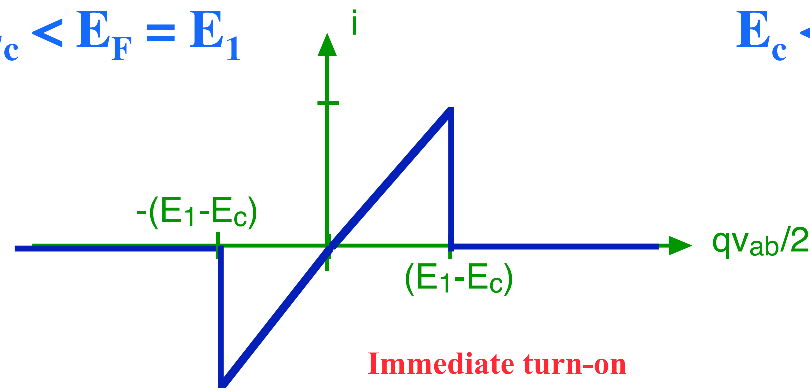


Note: Shape sharpens if tunneling through wires or boxes and/or from and to wells, wires, or boxes

Resonant Tunneling Diode - theoretical i-v, cont.

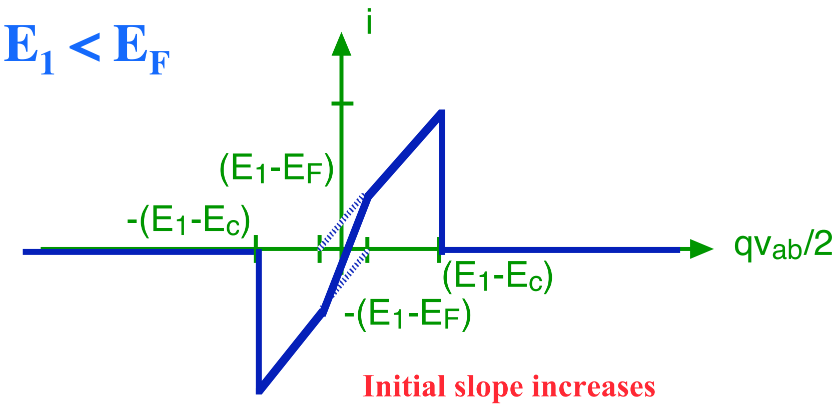
Variations in characteristics:

$E_c < E_F = E_1$



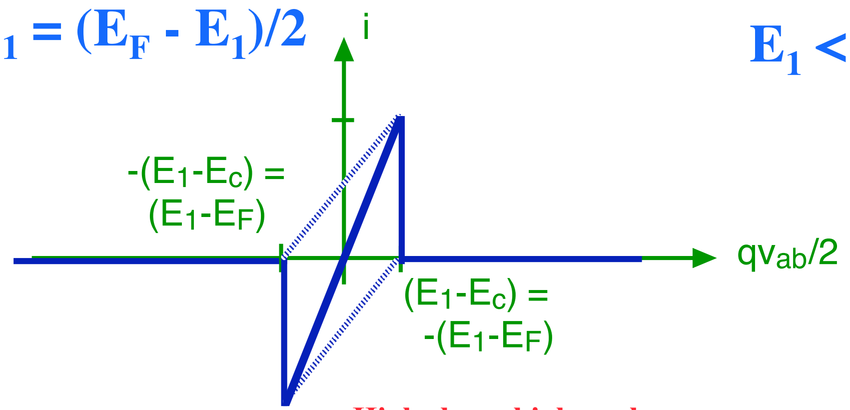
Immediate turn-on

$E_c < E_1 < E_F$



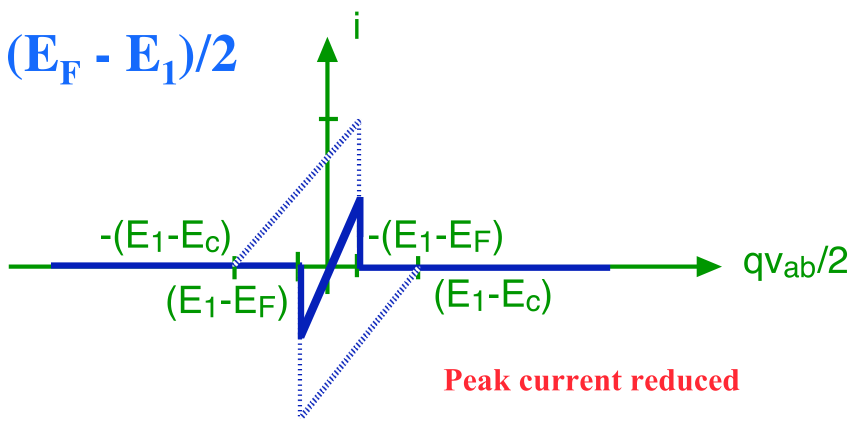
Initial slope increases

$E_1 = (E_F - E_1)/2$



High slope, high peak

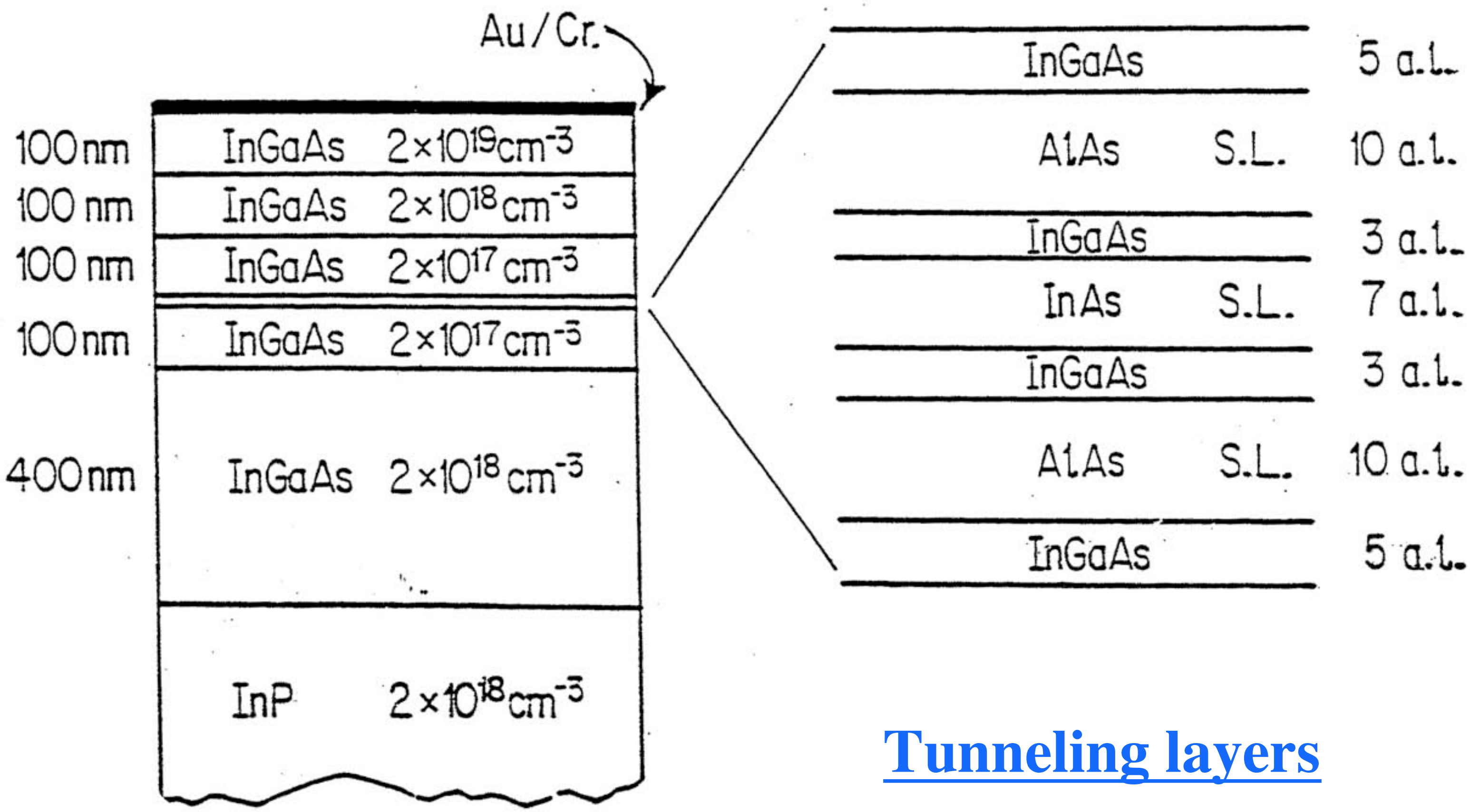
$E_1 < (E_F - E_1)/2$



Peak current reduced

Resonant tunneling diodes - an example

InGaAs/AlAs/InAs on InP:

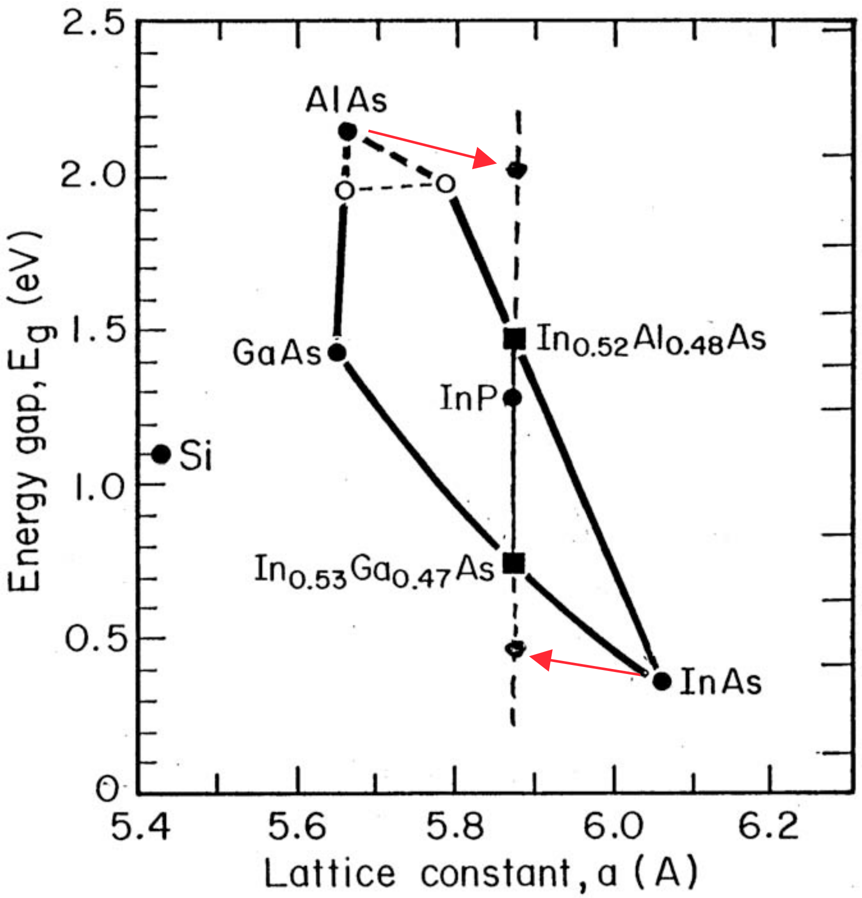


Tunneling layers

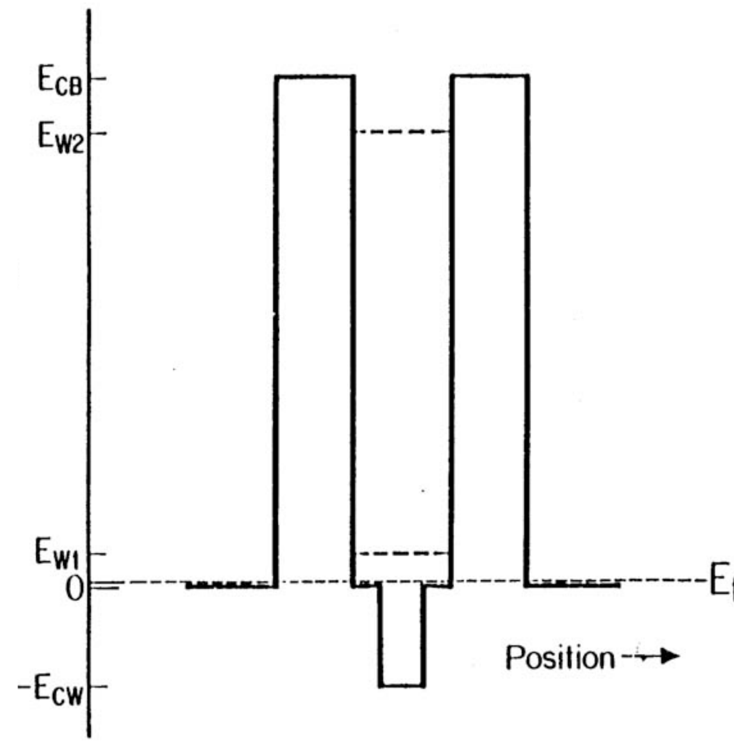
Overall structure

RTDs

InGaAs/AlAs/InAs on InP example cont.:



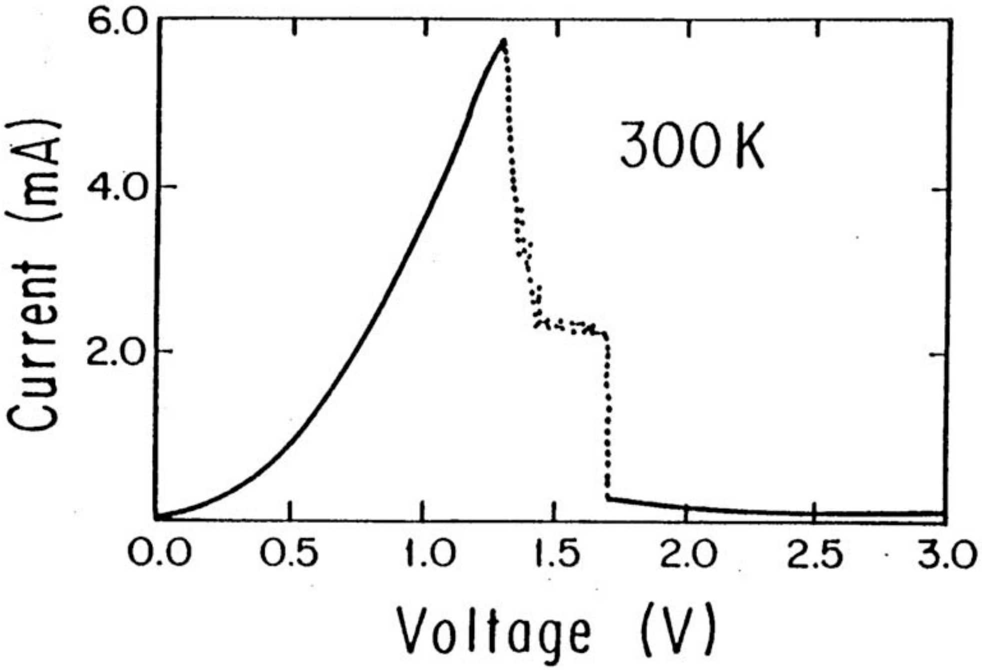
Materials system

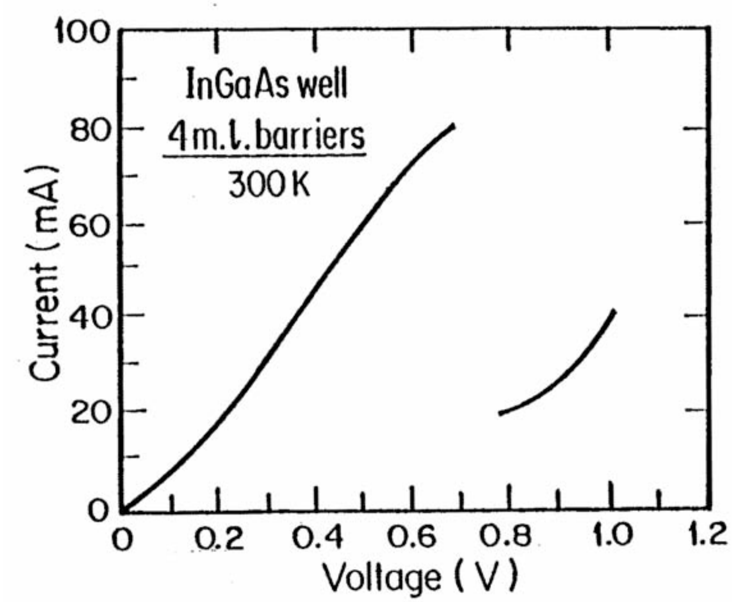


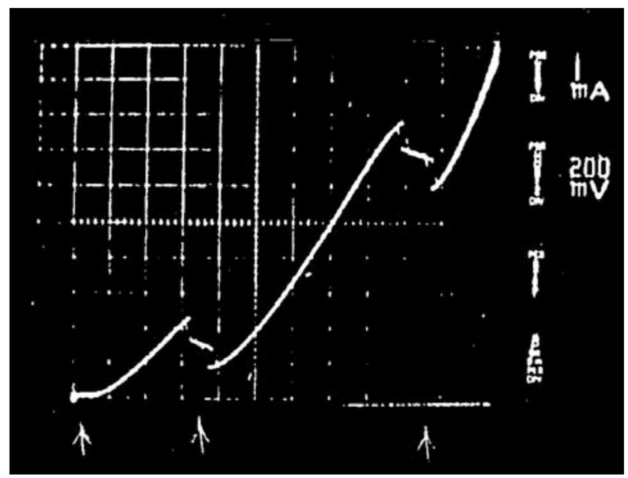
Band edge profile

RTDs

InGaAs/AlAs/InAs on InP example cont.:







Record results:

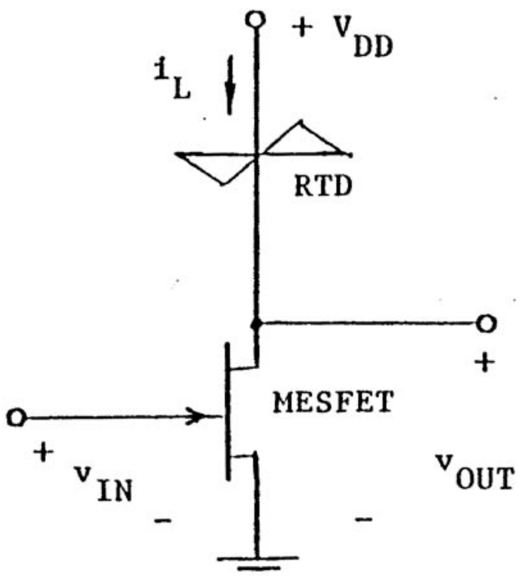
Above: $I_{peak}/I_{valley} = 50$

Upper right: high current density with 4 m.l. barrier

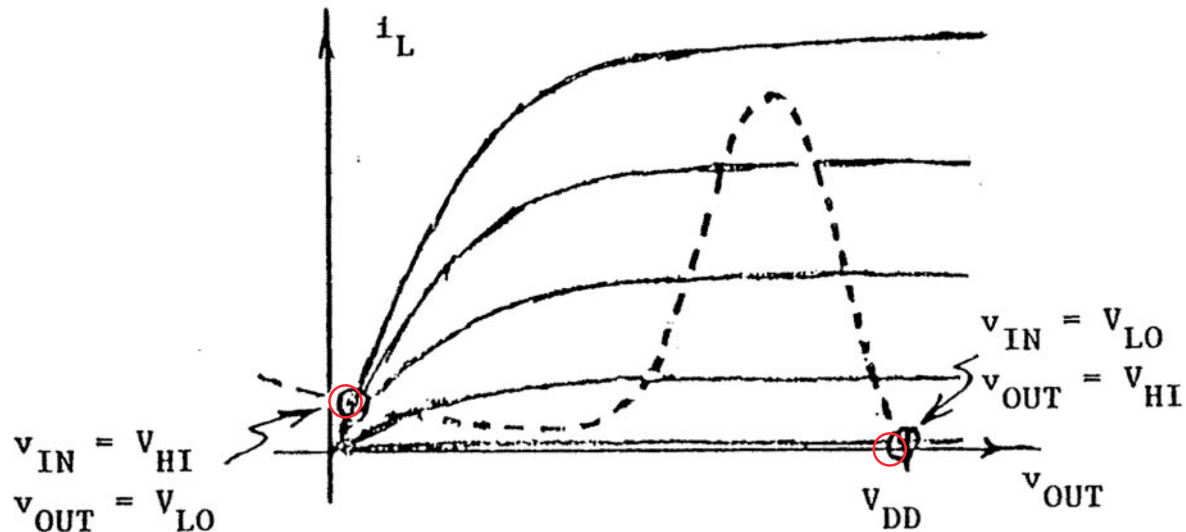
Right: three resonances seen in device with deep well

Resonant tunneling diodes - circuit applications

RTD Loaded Digital Inverters:



Schematic



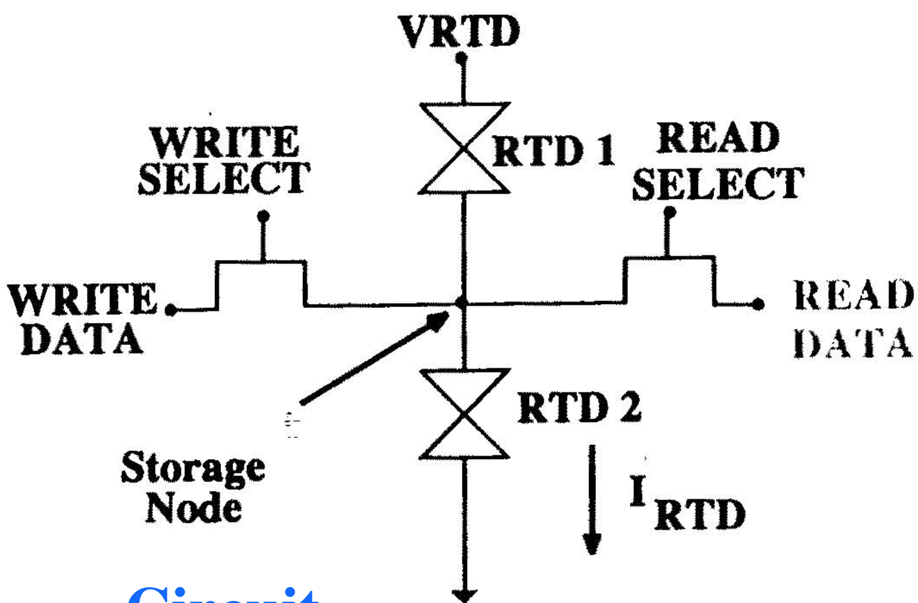
Characteristics

Concept: A III-V digital inverter cell with a low on-state current for low static power dissipation.

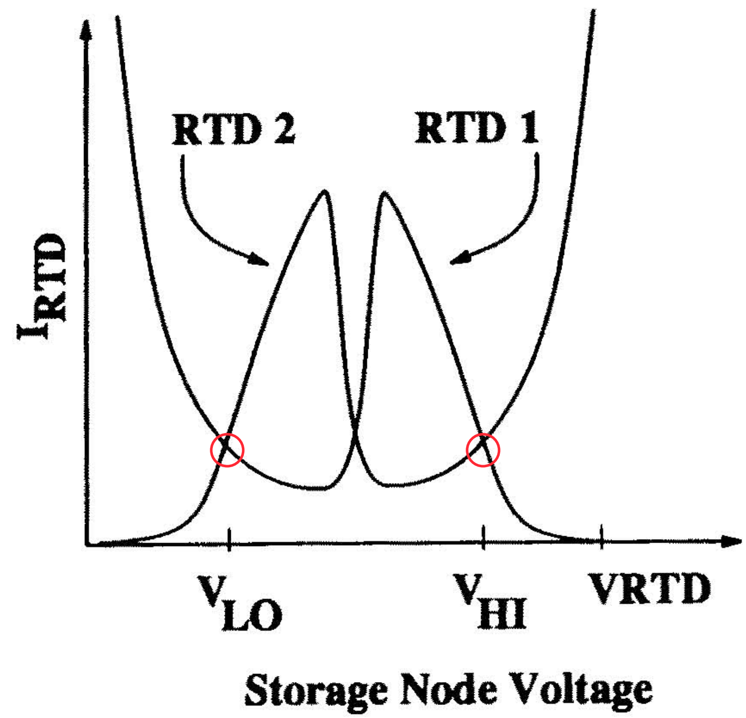
Evaluation: The low on-state current reduces the static power, but also reduces the switching speed because the charging current stays low until the RTD again reaches resonance. On balance the advantages of the circuit do not justify development costs.

Resonant tunneling diodes - circuit applications

RTD Static Memory Cell:



Circuit



Characteristics

Concept: A III-V static memory cell with a low device count and low static power dissipation.

Evaluation: Works and is fast; the difficulty is making RTDs reproducibly and integrating them with IC process.